AD-A112 869 CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN IL F/G 13/2
IN-PLACE NONDESTRUCTIVE EVALUATION METHODS FOR QUALITY ASSURANC--ETC(U)
MAR 82 J R CLIFTON, N J CARINO, P HOWDYSHELL
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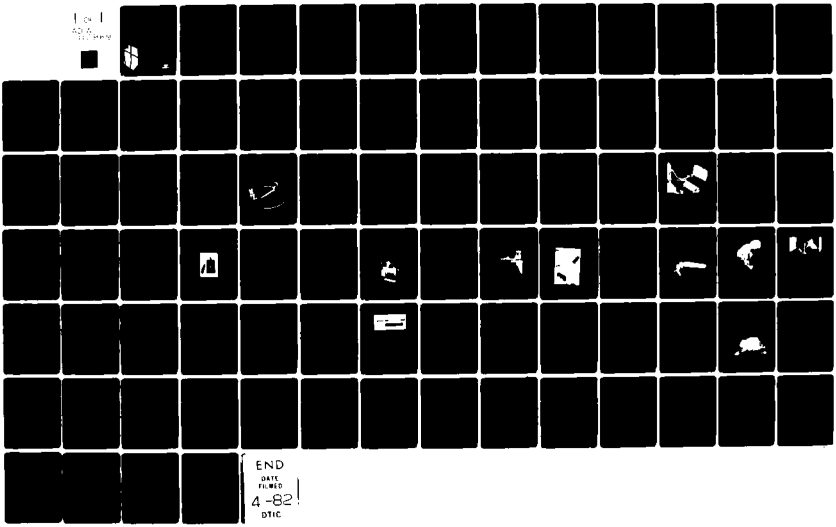

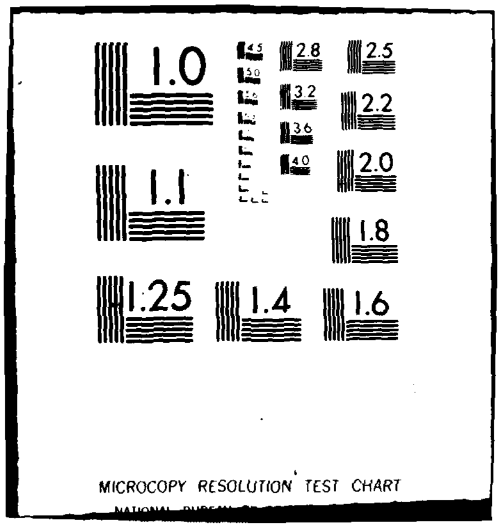
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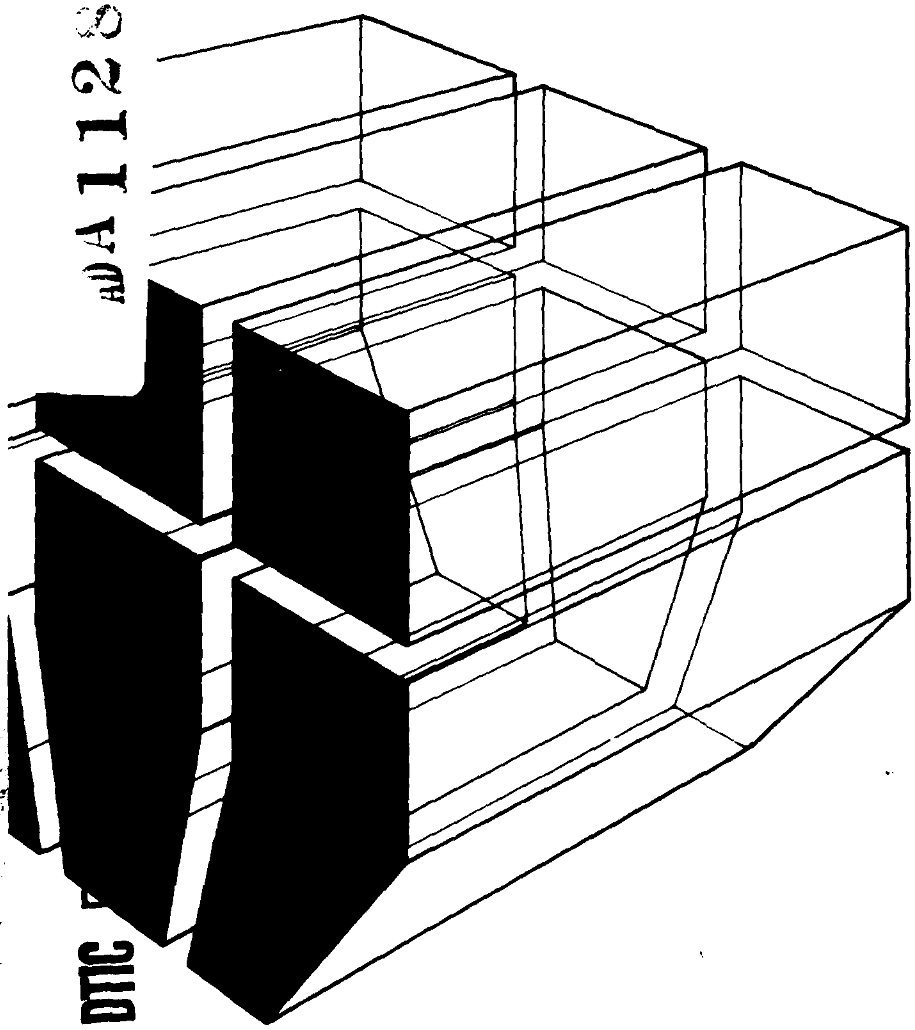
Technical Report M-305
March 1982
Techniques to Improve QC/QA Effectiveness

IN-PLACE NONDESTRUCTIVE EVALUATION METHODS FOR QUALITY ASSURANCE OF BUILDING MATERIALS



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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: CERL-TR-M-305
2. GOVT ACCESSION NO.: AD-A112 869
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): IN-PLACE NONDESTRUCTIVE EVALUATION METHODS FOR QUALITY ASSURANCE OF BUILDING MATERIALS
5. TYPE OF REPORT & PERIOD COVERED: FINAL
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s):
   James R. Clifton
   Nicholas J. Carino
   Paul Howdyshell
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS:
   U.S. ARMY
   CONSTRUCTION ENGINEERING RESEARCH LABORATORY
   P.O. Box 4005, Champaign, IL 61820
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 4A762731AT41-A-040
11. CONTROLLING OFFICE NAME AND ADDRESS
12. REPORT DATE: March 1982
13. NUMBER OF PAGES: 81
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

    Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES

    Copies are obtainable from the National Technical Information Service
    Springfield, VA 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

    nondestructive testing
    building materials
    buildings
    materials

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objectives of this report are: (1) to identify nondestructive evaluation (NDE) methods which can help building inspectors determine the quality and uniformity of in-place materials; and (2) to develop guidelines to assist inspectors in selecting appropriate NDE methods.

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Important properties of building materials and important performance requirements of systems and components are described; appropriate NDE methods are recommended. The NDE methods are explained in terms of the principles of their operation, the information they provide, the expertise required to use them, their typical applications, and their advantages and limitations.

FOREWORD

This work was performed for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), under Project 4A762731AT41, "Military Facilities Engineering Technology"; Task A, "Military Construction"; Work Unit 040, "Techniques To Improve QC/QA Effectiveness." The OCE Technical Monitor was Mr. E. Hunt, DAEN-MPC-E.

Appreciation is extended to Mr. Harry Berger, Office of Nondestructive Evaluation, National Bureau of Standards, for his suggestions and information.

Preparation of this report was sponsored by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). Dr. R. Quattrone is Chief of CERL-EM.

COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Techical Director.

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IN-PLACE NONDESTRUCTIVE EVALUATION METHODS FOR QUALITY ASSURANCE OF BUILDING MATERIALS

1 INTRODUCTION

Background

At U.S. Army Corps of Engineers job sites, the Resident Engineer must determine that the building contractor has followed proper construction practices. In addition, the Resident Engineer must make sure that the in-place building materials and components are acceptable.

The quality and uniformity of these materials depend on many processes.* For example, the standard practice for checking the quality of concrete includes measuring the slump, air content, and unit weight of plastic concrete, and the compressive strength of standard cylinders. However, these tests often do not reliably predict the quality of in-place concrete. The standard practice for checking the quality of in-place hardened concrete is to drill cores, which are examined and tested in a laboratory. This is time-consuming and expensive.

An inspector encounters similar difficulties in assessing the quality and uniformity of other building materials. Often these problems can be overcome by using nondestructive evaluation (NDE) methods to inspect in-place materials.

Since many types of NDE technology are available, the Office of the Chief of Engineers has asked the U.S. Army Construction Engineering Research Laboratory to summarize, for easy reference, the various methods of determining that proper quality control has been performed.

Some of the methods described in this report cause cosmetic damage to the material being inspected; e.g., the Windsor Probe and cast-in-place pullout methods. However, since the service life of the material is not affected, and the slight damage can be easily repaired, such methods are still considered nondestructive.

Objective

The objectives of this study are: (1) to identify NDE methods which can help the Resident Engineer's staff assure the quality and uniformity of in-place materials; and (2) to develop guidelines to assist inspectors in selecting appropriate NDE methods.

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* In this context, quality refers to the levels of the physico-chemical and engineering properties of a building material needed to meet the designed performance and service life. Uniformity refers to the range of variation in these properties existing within a specific building material.

Approach

The information in this report was gathered by a search of the literature on NDE methods, and by discussions both with researchers examining NDE techniques and with Resident Engineers' personnel.

Mode of Technology Transfer

The information in this document will be incorporated into an Engineer Manual in the 1110 series, or a Department of the Army Technical Manual in the 5-800 series.

Use of This Report

Chapter 2 contains Tables 1 through 13. Tables 1 through 12 list key properties of commonly used building materials and NDE methods for estimating the level of these properties or characterizing the materials. Operation, principles, and applications of the NDE methods are outlined in Table 13. These tables are intended to familiarize inspectors with NDE techniques, and to help personnel select appropriate methods. Chapter 3 provides more detailed information about the NDE techniques. The appendix lists standard test procedures which the American Society for Testing and Materials (ASTM) has issued for some NDE methods covered in this report.

To use the information in this report most efficiently, begin with Tables 1 through 12. If, for example, the quality and uniformity of in-place concrete seem questionable, further inspection could be justified. To learn about options for inspection, turn to Table 1; appropriate NDE methods are found in the second column. Four methods are listed for determining the general quality and uniformity of concrete: (1) Windsor Probe, (2) Schmidt Rebound Hammer, (3) ultrasonic pulse velocity, and (4) gamma radiography. (The methods are not ranked; the table simply provides a list.) To decide which of these methods would be appropriate for a specific application (considering factors such as equipment availability, cost factors, and information obtained), consult Table 13. The third column in Table 1, titled "Method No. in Table 13," gives the location of the four test methods in Table 13.

For more information before selecting any of the four methods, consult Chapter 3. The page numbers for the detailed discussions of the four methods are given in column 4 of Table 1.

The cross reference features of the tables can be used in the same way for information on other recommended NDE methods.

Note that the information in this report is not intended to supersede existing guide specifications. In cases of conflict, the guide specification is to be followed.

2 NDE TABLES

Building Materials, Components, and Systems

Major building materials, their important properties, and NDE methods for estimating these properties or for characterizing the materials are given in Tables 1 through 9. Materials considered are:

Table No.	Building Material
1	Concrete
2	Brick and mortar
3	Wood and lumber
4	Metals
5	Roofing
6	Paints and coatings
7	Soils
8	Sealants
9	Thermal insulation

The following building components and systems are covered in Tables 10 through 12:

Table No.	Components and Systems
10	Building envelope
11	Pipe and drainage systems
12	Heating, ventilation, and air conditioning systems

The main performance requirements are identified, and NDE methods for determining if these requirements are being met are listed.

The selection of the building materials, components, and systems addressed in this report was largely based on considerations of the amount of their use; the frequency and severity of problems caused by deficiencies in their quality, uniformity, or performance; and the value of using NDE methods to inspect the material, component, or system. For example, NDE inspection is not necessary to determine that a glass window is broken, while locating reinforcing steel in concrete is more readily done by NDE inspection than by coring. Personnel of the Center for Building Technology and the Office of Nondestructive Evaluation of the National Bureau of Standards, and of the U.S. Army Corps of Engineers assisted in the selection process.

In Tables 1 through 12, the column headed "Recommended NDE Methods" lists ways of testing various material properties. These tests are commonly used, and their limitations are well known. The column headed "Possible NDE Methods" lists NDE methods that may prove useful, but are still being assessed. In some cases, suitable NDE methods are not available -- e.g., for the inspection of the bond between a sealant and substrate (Table 8).

Survey of NDE Methods

The operation, principles, and applications of recommended NDE methods for inspecting building materials are outlined in Table 13. Self-explanatory NDE methods -- e.g., rulers and visual inspection methods -- from Tables 1 through 12 are not included.

Once construction inspectors become familiar with the advantages of using NDE, they may wish either to train people in their own organizations, or to get help from professional NDE inspectors. Comments on the expertise the user needs, equipment costs, and safety requirements are intended to help potential users decide which path to follow.

Table 1

NDE Methods for Inspecting Hardened Concrete

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Strength	Windsor Probe	27	49	
	Schmidt Rebound Hammer	21	58	
	Cast-in-place pullout	3	28	
	Maturity concept	14	39	
General quality and uniformity	Windsor Probe	27	49	Ultrasonic pulse echo
	Schmidt Rebound Hammer	21	58	Microwaves
	Ultrasonic pulse velocity	26	65	
	Gamma radiography	8	54	
Thickness				Microwaves (radar)
				Gamma radiography
				Ultrasonic pulse Velocity and echo
				Eddy current
Air content				Neutron density gage
Stiffness	Ultrasonic pulse velocity	26	65	
Surface texture	Visual		69	Microwaves
Density	Gamma radiography	8	54	Neutron density gage
	Ultrasonic pulse velocity	26	65	
Rebar size and location	Cover meter	4	35	Microwaves (radar)
	Gamma radiography	8	54	Ultrasonic pulse echo
Corrosion state of reinforcing steel	Visual		69	
	Electrical potential measurement	6	30	
Presence of subsurface voids or delaminations	Acoustic impact	2	27	
	Ultrasonic pulse echo	25	68	
	Gamma radiography	8	54	
	Ultrasonic pulse velocity	26	65	

Table 2

NDE Methods for Inspecting Brick and Mortar

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Integrity of masonry	Acoustic impact	2	27	Ultrasonic pulse echo
	Gamma radiography	8	54	Microwaves
	Probe holes with fiberscope	7	69	
	Ultrasonic pulse velocity	26	65	
Thickness of masonry	Probe holes	7	69	Eddy current Ultrasonic pulse echo
Reinforcing steel (location and size)	Cover meter	4	35	Ultrasonic pulse echo
	Gamma radiography	8	54	
Presence of inner grout	Probe holes	7	69	Ultrasonic pulse echo
	Gamma radiography	8	54	
	Acoustic impact	2	27	
	Ultrasonic pulse velocity	26	65	

Table 3

NDE Methods for Inspecting Wood and Lumber

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Integrity and general quality (including grade, mechanical properties, and assessment of insect, mechanical and decay damage)	Visual grading by certified grader* Proof loading	20	49	Acoustic emission Ultrasonic pulse velocity and echo Radiography Penetration hammer
Density	Ultrasonic pulse velocity	26	65	Penetration hammer Gamma and neutron radiography Nuclear density meter
Moisture content	Electric resistance probe	16	42	Nuclear moisture meter Surface hygrometers
	Capacitance instrument	15	43	Microwave absorption meter
Adhesive bond for laminated wood				Acoustic methods Thermal inspection (thermography) Radiography
Dimensions	Rulers, calipers, electronic measuring devices**			

*Perform on lumber before use; this method not described in Table 13.
**Because of their simplicity, methods not described in Table 13.

Table 4

NDE Methods for Inspecting Metals

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
A. Structural Metals				
Presence and location in other materials	Gamma radiography	8	54	Ultrasonic pulse echo
	Magnetic devices	12	35	
	Cover meter	4	35	
	Eddy current devices	5	32	
	Probe holes with fiberscope	7	69	
Type of metal	Magnetic devices		35	Chemical spot testing* Spark testing* Color* X-ray fluorescence analyzer
Cracks	Gamma radiography	8	54	
	Ultrasonic pulse echo	25	68	
	Magnetic particle	13	37	
	Liquid penetrant	11	70	
	Eddy current	5	32	
Corrosion condition	Electrical potential measurement	6	30	Eddy current Ultrasonic pulse echo
Loose bolts rivets and screws	Visual			Acoustic impact
B. Weld Defects				
Cracks	Ultrasonic pulse echo	25	68	
	Gamma radiography	8	54	
	Magnetic particle	13	37	
	Liquid penetrant	11	70	
Lack of fusion	Ultrasonic pulse echo	25	68	Magnetic particle
	Gamma radiography	8	54	

*For more information on these methods see Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

Table 4 (Cont'd)

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Slag inclusion	Gamma radiography Magnetic particle	8 13	54 37	Ultrasonic pulse echo
Porosity	Gamma radiography	8	54	Liquid penetrant Ultrasonic pulse echo
Incomplete penetration	Gamma radiography Ultrasonic pulse echo	8 25	54 68	
C. Pipes and Tanks				
Type of metal	See *Structural Metals*, above			
Wall thickness	Eddy current Ultrasonic pulse echo	5 25	32 68	
Leaks and continuity	Leak testing	10	38	
Corrosion condition	Electrical potential measurements	6	30	Eddy current Ultrasonic pulse echo

Table 5

NDE Methods for Inspecting Roofing Systems

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Composition				Cores -- laboratory analysis, specific gravity, solvent, odor, and chemical tests to distinguish between asphalt and coal tar pitch
Moisture content of insulation	Thermal inspection (thermography) Nuclear moisture meter Electrical resistance probe	23 17 16	61 44 42	Capacitance instrument Microwave
Permeability of roofing system	Flood or pond water on roof followed by using methods to measure contents of insulation			
Slope and drains				Flood or pond water on roof
Self supporting under design loads	Proof loading Wind uplift test (can be destructive)*	20	49	

*Type of proof loading.

Table 6

NDE Methods for Inspecting Paints and Coatings

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Number and type of layers	Tooke Gage	24	46	
Film thickness				
Metal:	1. Magnetic field testing (thickness gage)	12	35	
	2. Eddy current	5	32	
Wood:	Tooke Gage	24	46	
Integrity (Pin holes)				
Metal:	Pin hole (holiday) detector	19	48	
Wood:	Field microscope		69	
Bond to substrate				Adhesion tester Scratch adhesion test Thermal inspection (thermography)
Surface preparation				Tooke Gage Field microscope
General quality color, reflectance, blistering, etc.				Photography -- comparison with standard Measurement of reflectivity Thermal inspection (thermography)

Table 7

NDE Methods for Inspecting Soils

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Adequate drainage	Visual check of grade and topography*			
Adequacy of backfill				Microwave to detect cavities in backfill
Density and compaction	Seismic testing Nuclear density meter	22 18	56 44	
Moisture contents	Nuclear moisture meter	17	44	Electrical resistance probe

*Because of its simplicity, method not described in Table 13.

Table 8

NDE Methods for Inspecting Sealants

Property	Recommended Methods	Method No. in Table 13	NDE Method Described on Page
Water permeability (infiltration)	Electrical resistance meter	16	42
	Capacitance instrument	15	43
General quality and workmanship	Move water jet up the building wall (from bottom to top) and observe water infiltration -- use methods given for testing for water permeability		
Bond to substrate			

Table 9

NDE Methods for Inspecting Thermal Insulation

Property	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Performance	Thermal inspection (infrared thermography)	23	61	
Location	Thermal inspection (infrared thermography)	23	61	
	Fiberscope	7	69	
Moisture contents				Capacitance instrument Electrical resistance meter Thermal inspection
Corrosiveness	Measure electrical potential of metals in contact with insulation	6	30	

Table 10

NDE Methods for Inspecting the Building Envelope

Component or System	Main Performance Requirements	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Walls and Ceilings	No penetration by rain water				1. Electrical capacitance 2. Fiber scope 3. Nuclear moisture meter 4. Resistance probe
	Retard heat transmission	Thermal inspection	23	61	Thermal inspection (thermography)
Foundation and Basement	Supports building				
	Prevents settlement	Visual crack survey Level readings -- change with elapsed time* Strain gage buttons on cracks* Photographic recording of cracks with elapsed time*			
	Prevents upward movement of moisture	Moisture meter			
	Prevents basement slab movement	Visual and/or level readings - change with elapsed time*			
Roof	No penetration by rain water	Nuclear moisture meter	17	44	Capacitance instrument
		Thermal inspection (thermography)	23	61	
	Self-supporting under design loads	Proof loading	20	49	
	Retard heat transmitting	Thermal inspection (thermography)	23	61	

Table 10 (Cont'd)

Component or System	Main Performance Requirements	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Floor	Levelness	Level readings -- change with elapsed time* Carpenter's level*			
	Supports design service loads	Proof loading	20	49	
	Joining details and construction practices and materials				Gamma radiography Fiberscope

*Self-explanatory; not described in Table 13.

Table 11

NDE Methods for Inspecting Pipe and Drainage Systems

Performance Requirements	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Does not leak	Leak testing	10	38	
Proper flow rate	Measure volume of water flowing during time interval*			Flow meter connected to outlet
Proper flow pressure				Hydrostatic pressure gage
Dielectric joints between dissimilar metals	Measurement of electrical resistance across joint			Inspection by fiberscope
Prevention of back flow of gases	Di[illegible]ment of [illegible] trap*			Determination of pressure of proper component

*Self-explanatory; not described in Table 13.

Table 12

NDE Methods for Inspecting Heating, Ventilation, and Air Conditioning Systems

Performance Requirements	Recommended NDE Methods	Method No. in Table 13	NDE Method Described on Page	Possible NDE Methods
Proper air flow level	Air flow measurement*			
Air ducts properly sealed	Leak detection	10	38	Sound Amplification Fiberscope

*Self-explanatory; not described in Table 13.

Table 13

Operation, Principles, and Applications of Commonly Used NDE Methods for Inspection of Building Material

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
1. Acoustic Emission	During crack growth or plastic deformation, the rapid release of strain energy produces acoustic (sound) waves that can be detected by sensors attached to the surface of a test object.	Continuous monitoring of structure during service life to detect impending failure; monitoring performance of structure during proof testing.	$10,000 for single pickup, up to $100,000 for multi-channel pickup.	Extensive knowledge required to plan test and to interpret results.	Monitors response of as-built structure to applied load; capable of detecting onset of failure; capable of locating source of possible failure.	Requires means of loading structure; complex electronic equipment is required; access to surface is required.
2. Acoustic Impact (Hammer Test)	Surface of object is struck with a hammer (usually metallic). The frequency and damping characteristics of the "ringing" can indicate the presence of defects.	Detect delaminations or disbonds in composite systems; detect voids and cracks in materials, e.g., hammer technique to detect defective masonry units; "chain drag" method to detect delaminations in concrete pavements.	Negligible for manual technique, $3000 for measuring devices.	Low to use, but experience needed for interpreting results.	Portable; easy to perform test; electronic device not needed for qualitative results.	Geometry and mass of test object influences results; poor discrimination; reference standards required for electronic testing.
3. Cast-in-Place Pullout	Measure the force required to pull out steel rod with enlarged head cast in concrete. Pullout forces produce tensile and shear stresses in concrete.	Estimation of compressive and tensile strengths of concrete.	$1000 to $4000.	Low, can be used by field concrete testers and inspectors.	Only NDE method which directly measures in-place strength of concrete. Appears to give good prediction to concrete strength.	Pullout devices must be inserted during construction. Cone of concrete may be pulled out, necessitating minor repairs.
4. Cover-Meter	Presence of steel affects the magnetic field of a probe. Closer probe is to steel, the greater the effect. Principle of operation is similar to eddy current method.	Determination of presence, location and depth of rebars in concrete and masonry units.	$800 to $1500.	Moderate. Easy to operate. Need training to interpret results.	Portable equipment, good results if concrete is lightly reinforced.	Difficult to interpret results if concrete is heavily reinforced or if wire mesh is present.
5. Eddy Current	An electrically excited coil induces eddy current flow and an associated electromagnetic field in metal. Flaws alter induced electromagnetic field which in turn alters the impedance of the excitation coil. Change in coil impedance indicates presence of flaw or anomaly.	Inspection of metal parts for cracks, voids, inclusions, seams, and laps; measurement of thickness of nonmetallic coating on metals; detection of improper alloy composition.	Minimum of $3000.	Moderate.	Extremely sensitive to change in properties and characteristics of metal; portable.	Requires calibration with standards; limited depth of penetration; only applicable to metals; sensitive to geometry of part.

Table 13 (Cont'd)

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
6. Electrical Potential Measurements	Electrical potential of steel reinforcement measured. Potential indicates probability of corrosion.	Determining condition of steel rebars in concrete.	\$1000 to \$2000.	Moderate. User must be able to recognize problems.	Portable equipment. Field measurements readily made. Appears to give reliable information.	Does not provide information on rate of corrosion. Requires access to reinforcing bars.
7. Fiberscope (Endoscope)	Bundle of flexible, optical fibers with lens and illuminating systems is inserted into small bore hole--permits view of interior of cavities.	Check condition of materials in cavity, such as thermal insulation installed in wall cavities, pipes and electrical wiring in cavity walls; check for unfilled cores in reinforced masonry construction; check for voids along grouted stressed tendons.	\$3000 to \$6000.	Low.	Direct visual inspection of otherwise inaccessible parts is possible.	Probe holes usually must be drilled; probe holes must connect to a cavity.
8. Gamma Radiography	Gamma radiation attenuates when passing through a building component. Extent of attenuation controlled by density, and thickness of the materials of the building component. Photographic film record usually made, which is analyzed.	Locating internal cracks, voids and variations in density and composition of materials. Locating internal parts in a building component, e.g., reinforcing steel in concrete.	\$5000 to \$10,000.	Must be operated by trained and licensed personnel.	Portable and relatively inexpensive compared to X-ray radiography; internal defects can be detected; applicable to a variety of materials.	Radiation intensity cannot be adjusted; long exposure times may be required; dangerous radiation; two opposite surfaces of component must be accessible.
9. Indentation Hardness Test	Pointed probe is mechanically forced into surface of a material, usually a metal, under a specified load. The depth of indentation is measured, and strength of material may be estimated.	Determination of effectiveness of heat treatment on hardness of metals. Estimating tensile strength of metals.	\$600 to \$4000.	Low.	Portable equipment available; fast and easy test to perform.	Conversion tables give only approximate tensile strengths; feasibility of testing limited by size and geometry of component.
10. Leak Testing	Telltale substances added to piping system under pressure reveal presence of leaks. Sound amplification to detect leak noise.	Detection of leaks in pipes carrying fluids.	Wide range depending on detection method. \$100 to \$5000.	Low to high depending on application.	Can locate leaks too small to be found by any other NDE method.	Difficult to determine position of leaks in pipes hidden in wall or floor cavities.

Table 13 (Cont'd)

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
11. Liquid Penetrant Inspection	Surface is covered with a liquid dye which is drawn into surface cracks and voids. Developer is applied to reveal presence and location of flaws.	Detection of surface cracks and flaws. Usually used to inspect metals.	$50 to $250 per 100 linear feet of inspection.	Low.	Inexpensive; easy to use; can be applied to complex parts; results are easy to interpret.	Detects only surface flaws; false indications possible on rough or porous materials; surface requires cleaning prior to testing.
12. Magnetic Field Testing	An electrically energized primary coil is brought near test object. A voltage is induced in a secondary coil, and its magnitude is compared to a reference standard. Magnetic properties of test object affect induced voltages.	Distinguishing between steels based on differences in composition, hardness, heat treatment, or residual stresses; locating hidden magnetic parts; measuring thickness of nonmagnetic coatings or films.	$3000.	Low to moderate, depending on application.	Portable; rapid test; easily detects magnetic objects even if embedded in nonmagnetic material.	Applicable only to ferromagnetic alloys; reference standards and calibration may be required for some applications.
13. Magnetic Particle Inspection	Presence of discontinuities in ferromagnetic material will cause leakage field to be formed at or above the discontinuity when the material is magnetized. The presence of the discontinuity is detected by use of finely divided ferromagnetic particles applied over the surface. These form an outline (termed indication) of the discontinuity.	Used most often to detect fatigue cracks in in-service metal components and inspection during production control. Applicable to inspecting welds.	Minimum of $2000.	Expertise required to plan nonroutine tests. Moderate expertise to perform test.	Capable of detecting subsurface cracks if they are larger than surface cracks; size and shape of component poses no limitation; portable equipment available.	Non-ferromagnetic metal cannot be inspected; coatings affect sensitivity; demagnetization may be required after testing.
14. Maturity Concept	The early age strength development of concrete is related to the combined effect of temperature and time.	Prediction of the compressive strength of concrete during the construction phase.	Maturity meter costs around $2000.	Expertise required to develop maturity-strength relationships.	Accounts for in-place temperature history. Field measurements simple to perform.	Calibration strength-maturity curve must be developed. No direct measure of in-place strength. Location of temperature sensors must be carefully selected.
15. Moisture Meter--Capacitance	Water affects the dielectric constant and the dielectric loss factor of materials. Measurement of either property can be used to estimate moisture contents.	Measurement of moisture contents of timber and roofing materials.	$1500	Low to use but experience needed to plan test.	Portable; simple to operate; effective over a wide range of moisture contents.	Measurement is only of surface layer; calibration required; results affected by roofing aggregates; many factors affect accuracy.

Table 13 (Cont'd)

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
16. Moisture Meter--Electrical Resistance	Electrical resistance between two probes inserted into test component is measured. The resistance decreases with increased moisture contents.	Measurement of moisture contents of timber, roofing materials, and soils.	$300 to $1000.	Low.	Equipment is inexpensive, simple to operate, and many measurements can be rapidly made.	Not reliable at high moisture contents; needs to be calibrated; precise results are not usually obtained.
17. Moisture Meter--Neutron	Fast neutrons are slowed by interactions with hydrogen atoms. Backscattered slowed neutrons are measured, the number of which is proportional to the number of hydrogen atoms present in a material.	Moisture content measurements of soil and roofing materials.	$4000 to $6000.	Must be operated by trained and licensed personnel.	Portable; moisture measurements can rapidly be made on in-service materials.	Only measures moisture content of surface layers (50 mm); dangerous radiation; hydrogen atoms of building materials are measured in addition to those of water.
18. Nuclear Density Meter	Gamma rays are used to measure mass density. The energy loss of the emitted gamma rays is proportional to the mass density of the material through which the rays pass.	Measurement of density of soils.	$4000 to $6000.	Must be operated by trained and licensed personnel.	Portable; density measurements can be made without disturbing the soil.	Calibration necessary; dangerous radiation; only measures density of surface layers.
19. Pin Hole (Holiday) Detector	One electrode is connected to a conductive substrate, another electrode (a moistened sponge) is passed directly over a coating. An alarm is sounded when a pin hole (holiday) is encountered which completes the electrical circuit.	Determining the presence of pin holes in nonconductive coatings over metals.	$200	Low.	Simple to operate; portable.	Results are qualitative, e.g., there is no measure of the size of the pin hole.
20. Proof Loading	Structure or system is subjected to loads and response is measured.	Determining safe capacity and integrity of structures. Leak testing of pressure vessels and plumbing.	Wide, depending on application; often high.	Depends on nature of tests; can be high.	Entire structure can be tested in its "as-built" condition.	Can be very costly; instrumentation required to measure response; careful planning required; can damage structure.

Table 13 (Cont'd)

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
21. Rebound Hammer	Spring-driven mass strikes surface of concrete and rebound distance is given in R-values. Surface hardness is measured.	Estimation of compressive strength, uniformity and quality of concrete.	$250 to $600.	Low, can be readily operated by ordinary field personnel.	Inexpensive. Large amount of data can be quickly obtained. Good for determining uniformity of concrete.	Results affected by condition of concrete surface. Does not give precise prediction of strength.
22. Seismic Testing	Integrity of material evaluated by analysis of shock wave transmission and effects. Shock wave induced by explosive charges and transmission detected by transducers.	Determination of soil densities and variation in densities. Also vibrational characteristics of buildings can be determined.	Wide, depending on amount of information desired.	Experience required to plan test and to interpret results.	Large area of soil and entire structure in its "as-built" condition can be tested.	If incorrectly placed, explosive charge could damage structure. Care must be exercised in handling explosives.
23. Thermal Inspection	Heat sensing devices are used to detect irregular temperature distributions due to presence of flaws or inhomogenities that have different impedances to heat flow in the material or component. Contours of equal temperature (thermography) or temperatures (thermometry) are measured over the test surface with contact or noncontact detection devices. A common detection device is an infrared scanning camera.	Detection of heat loss through walls and roofs; detection of moisture in roofs; detection of delaminations in composite materials.	$30,000 for infrared scanning camera. Less expensive hand-held equipment becoming commercially available.	Moderate to extensive depending on nature of test.	Portable; permanent record can be made; testing can be done without direct access to surface and large areas can be rapidly inspected using infrared cameras.	Costly equipment; reference standards needed; means of producing thermal gradient in test component or material is required.
24. Tooke Gage	A V-groove is cut into the coating, and an illuminated magnifier equipped with a reticle in the eyeplace is used to measure the number and thickness of the films.	Measurement of the number and thicknesses of paint layers.	$1300	Low.	Simple to operate; portable; measurement can be made with any type of substrate.	Small scratch is made in coating and the substrate is exposed.
25. Ultrasonic Pulse Echo	Pulsed compressional waves are induced in materials, and those reflected back are detected. Both the transmitting and receiving transducers usually are contained in the same probe.	Inspecting metals for internal discontinuities. Some work has been performed on the use of the pulse echo method to inspect concrete.	Minimum of $5000.	High level of expertise required to interpret results.	Portable; internal discontinuities can be located and their sizes estimated.	Good coupling between transducer and test substrate critical; interpretation of results can be difficult. Calibration standards required.

(Table 13 (Cont'd)

Method	Principle	Main Applications	Equipment Cost	User Expertise	Advantages	Limitations
26. Ultrasonic Pulse Velocity	Based on measuring the transit time of an induced pulsed compressional wave propagating through a material.	Estimation of the quality and uniformity of concrete.	$4000 to $6000.	Low level required to make measurements.	Excellent for determining the quality and uniformity of concrete. Test can be performed quickly.	Does not provide precise estimate of strength. Skill required in analysis of results. Moisture variations can affect results.
27. Windsor Probe	Probe fired into concrete and depth of penetration is measured. Surface and subsurface hardness measured.	Estimations of compressive strength, uniformity, and quality of concrete.	$1000 plus cost of probes.	Low, can be operated by ordinary field personnel.	Equipment is simple and durable. Good for determining quality of concrete.	Slightly damages small area. Does not give precise prediction of strength.
28. X-ray Fluorescence Analyzer	Material is irradiated with a radioactive isotope and absorbed energy is re-emitted as X-rays characteristic of elements present in material.	Determination of the elements present in material.	$7000 to $20,000.	Extensive knowledge of technique required for calibration; moderate to conduct field tests.	Rapid analysis; test can be performed on installed materials; portable.	Periodic calibration with reference standard required; not capable of detecting all elements; analysis of small region per test.
29. X-ray Radiography	Similar to gamma radiography, except X-rays are used.	To identify hidden construction features in wooden structures.	Field equipment is probably over $5000.	Should be operated by trained personnel because of radiation.	Portable equipment available, intensity of radiation can be varied.	Dangerous radiation; portable units have low intensities and field applications limited to wooden and thin components; opposite surface of component must be accessible.

3 DESCRIPTION OF NDE METHODS

Acoustic Emission Method

In this method, stress waves originating within the test object are detected by surface transducers.[1] The acoustic waves result from the sudden release of stored strain energy when either pre-existing or newly created flaws propagate under the action of an applied stress field. The types of flaw propagation that can be detected include dislocation movement in metals and microcrack growth in metals or brittle solids such as concrete. Thus, acoustic emission can indicate the start of mechanical failure -- i.e., yielding or fracture. The test object must undergo stress so that flaws will appear; static flaws are not detected by acoustic emission.

Description of Method

Acoustic emission testing is a passive technique; only an acoustic wave detection instrument is required. The acoustic waves, which may have a frequency range from audible to ultrasonic, are detected by piezoelectric transducers attached to the surface of the test object. The origin of the flaw growth can be detected by a transducer anywhere on the test object (provided that there is enough wave amplitude to be detected). Thus, the location of transducers relative to the pre-existing flaws is not critical in this method. The transducers generally detect waves in the frequency range of 50 kHz to 10 MHz.[2] Detected signals are amplified; the amount of necessary amplification depends on the source of the acoustic emission. Signals from dislocation movement require greater amplification than signals from microcrack propagation. After amplification, the acoustic emission activity is processed and displayed. The most useful displays are the rate of acoustic emission events, or the cumulative number of events plotted as a function of a pertinent parameter, such as time, applied load, or number of load cycles. Growth of microcracks as small as 10^{-5} in. (2.5×10^{-4} mm) can be detected, while the minimum static flaw detectable by ultrasonic or radiographic methods is about 0.001 in. (0.025 mm).

Applications

The method has been used to monitor the in-service behavior of pressure vessels (including nuclear reactors), to detect the onset of rapid crack propagation under fatigue loading or caused by stress corrosion, and to monitor the response of systems to proof-load tests. Because acoustic emissions give forewarning of ultimate failure, the technique can be used to signal when loads should be reduced to prevent total failure. By using both multiple pickup of acoustic signals with transducers at different locations and electronic data processing, regions of high acoustic emission activity can be pinpointed, and the critical "weak link" in the system located.

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[1] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

[2] Metals Handbook, Vol 11.

Advantages

The most significant advantage of the acoustic emission method is that it gives the response of the total structure or system (in "as-built" condition) to applied loads. By observing the acoustic emission activity as loads are applied, one can find the extent of internal material degradation (yielding or fracture) as a function of load. Generally, the stage of incipient failure can be determined because this is usually accompanied by a rise in the acoustic emission rate and a rapid increase in the cumulative number of emissions.

Limitations

A major difficulty in interpreting acoustic emission results is the separation of signals caused by the loading system or by microscopic slippage at joints in the test object from the signals produced by flaw propagation in the material. Users of the technique must be aware of all the possible extraneous acoustic signals that may be detected by the transducers, and must be careful not to confuse them with signals due to flaw growth. Some background noise may be eliminated by using low frequency filters, but other noise may require more complicated methods. A high level of skill is required to properly plan an acoustic emission inspection program. Equipment costs vary from moderate ($10,000) to very expensive, depending on whether a single- or multiple-pickup system is required for the particular application.

Acoustic Impact Method

Description of Method

Acoustic impact is the oldest and simplest form of acoustic inspection. In this method, audible stress waves are set up in a test object by mechanical impact; the frequency and damping characteristics of the vibrations can be used to infer the integrity of the test object.[3] In its most unsophisticated form, the test object is struck with a hammer, and the operator listens to the "ringing" caused by the resonant vibration of the object. In a more sophisticated form, a transducer is attached to the test object, and an amplifier and display unit are used to produce a visual display of the frequency and damping characteristics of the "ringing." By comparing the output with a standard representing acceptable quality, a decision is made regarding the integrity of the object.

Applications

This method can be used to detect hollow zones and delaminations in concrete and masonry structures, or it may be used to find studs behind wallboard. It also has been used to detect delaminations in laminar and composite materials.

[3] R. J. Botsco, "Specialized NDT Methods," Lesson 12, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977).

Advantages

The equipment required to carry out the test is relatively inexpensive, and the test can be done easily.

Limitations

Because the "ringing" can be affected by the mass and geometry of the test object, an experienced operator may be needed to correctly interpret the results.

Cast-in-Place Pullout

The pullout test measures the force required to pull out a steel insert, with an enlarged end, which has been cast in the concrete (Figure 1). The concrete is subject to complex stresses by the pullout force, and a cone of concrete is removed at failure. The pullout forces are usually related to the compressive strength of the concrete, with the ratio of pullout strength (force divided by surface area of the conic frustum) to compressive strength being in the range of 0.1 to 0.3. Correlation graphs are used to relate

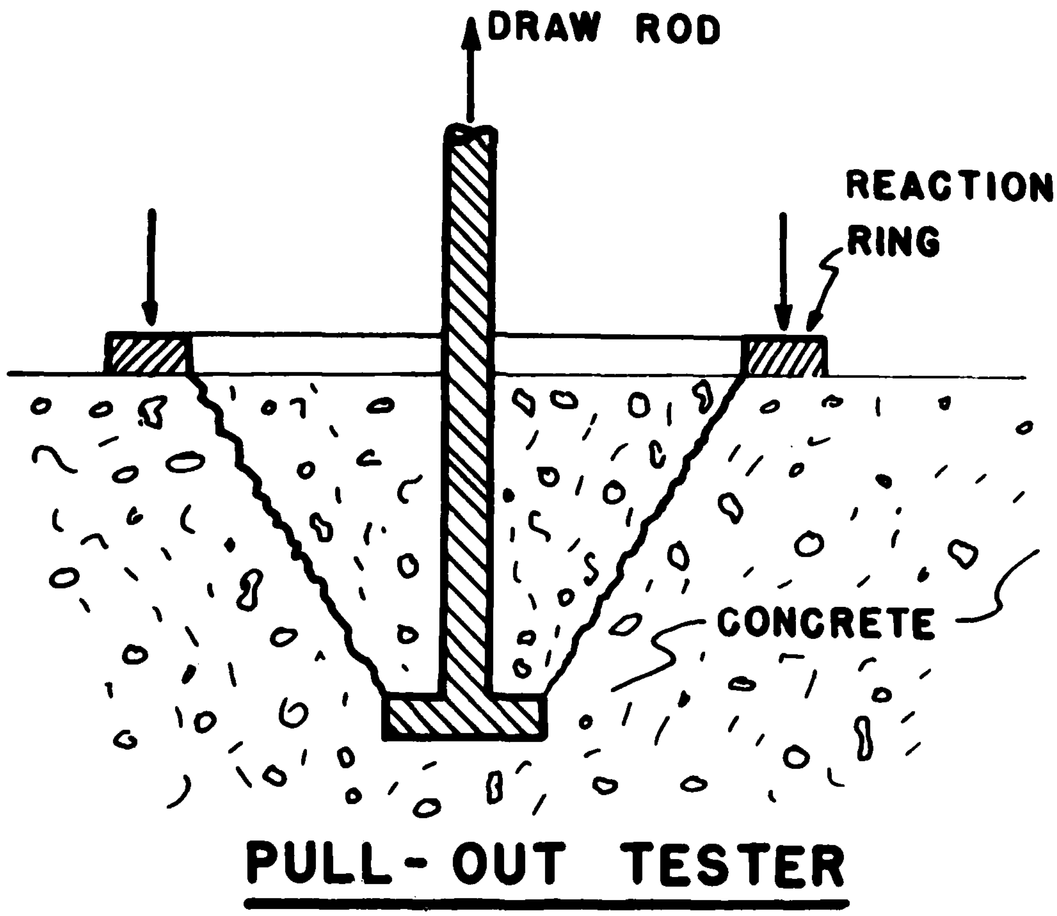

Figure 1. Schematic of cast-in-place pullout device.

pullout force to compressive strength. There are several commercially available test apparatus for measuring the pullout resistance of concrete. Equipment prices vary from $1000 to $5000.

Description of Method

ASTM has recently issued a tentative test method, C 900-78T, which describes in detail the pullout assembly and gives allowable dimensions.[4] The pullout insert is cast-in-place during placing of fresh concrete. The insert is either pulled completely out of the concrete, or pulled until maximum load is reached, with a manually operated hollow tension ram exerting pressure through the steel reaction ring. Components of one possible test apparatus for pulling out the insert are shown in Figure 2. Testing and calculation

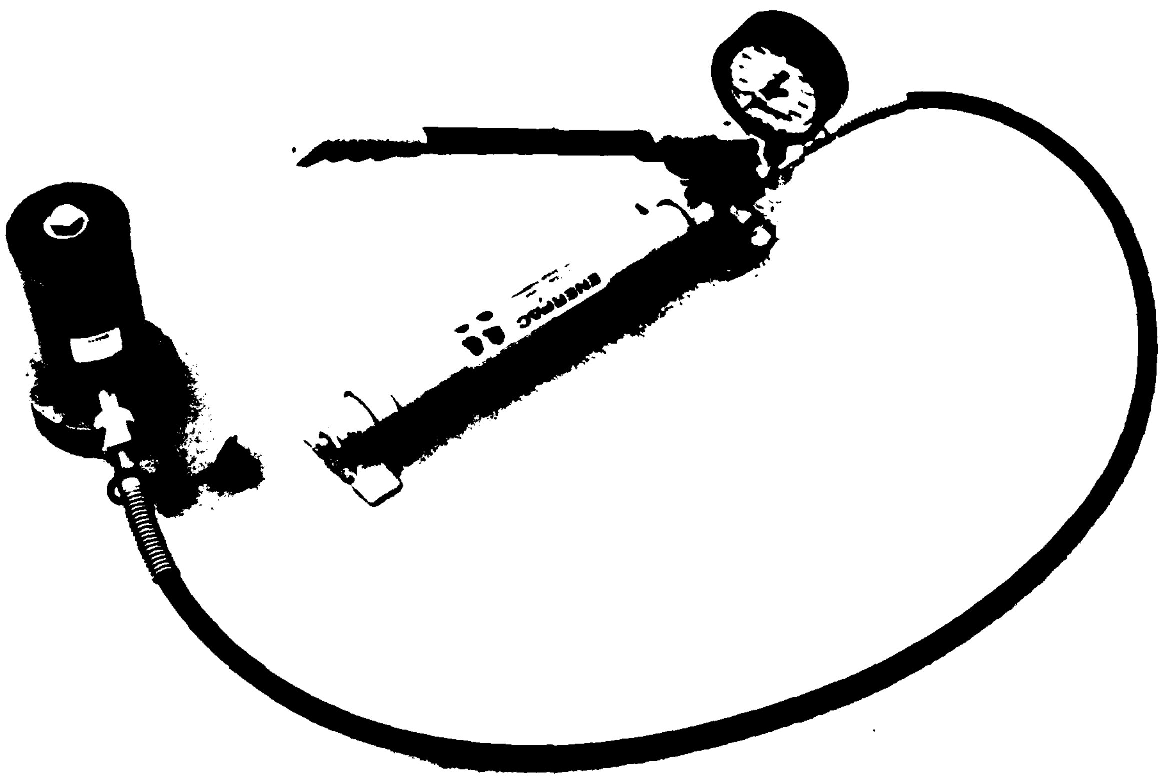

Figure 2. Components of one type of apparatus for performing pullout test.

[4] Tentative Test Method for Pullout Strength of Hardened Concrete, American Society for Testing and Materials (ASTM) C 900-78T (1978).

procedures are also given in ASTM C 900-78T. Techniques have been developed so that the inserts can be embedded deep in concrete, thereby permitting testing of the interior concrete.

Because the pullout insert is usually cast-in-place during placing of the fresh concrete, these tests must be planned in advance. Alternatively, hardened concrete can be drilled to receive the pullout insert. This necessitates drilling through the bottom or backside of a concrete slab, for example, to the proper depth and width to permit the insertion of the enlarged head. A smaller hole, permitting insertion of the steel shaft, is drilled through the remaining portion of the concrete slab. The insert is placed through the bottom of backside, and the test is performed.

Reliability of Method

Malhotra and Richards have shown that the pullout method can reliably estimate the compressive strength of concrete.[5] Malhotra found that the coefficients of variation for pullout test results were in the same range as obtained from testing standard cylinders in compression. Correlation coefficients of 0.97 to 0.99 have been obtained for normal weight concrete from curve fitting of pullout and compression test results.

Advantages

The pullout technique is the only nondestructive test method which directly measures a strength property of concrete in place. The measured strength is generally thought to be a combination of tensile and shear strengths. The major disadvantage of the pullout test is that a cone of concrete is sometimes pulled out, necessitating minor repairs. However, if the pullout force is quickly released just when failure begins, the concrete cone will not be torn loose, and no repairs will be required. Another disadvantage is the need to plan where inserts are to be located and to make provisions for them before placing concrete. The feasibility of drilling holes into hardened concrete and inserting pullout devices is being explored.[6] This would eliminate the need to install the inserts prior to placing concrete.

Electrical Potential Measurements

Information on the corrosion state of metals can be obtained from measuring the electrical potential of the metal using a standard reference electrode and a voltmeter. If the metal has a certain electrical potential, active corrosion is very likely.

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5 V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, American Concrete Institute (ACI) Monograph No. 9 (1976); O. Richards, Pullout Strength of Concrete in Reproducibility and Accuracy of Mechanical Testing, ASTM STP-626 (1977), pp 32-40.

6 G. Mailhot, A. Bisaillon, G. G. Carette, and V. M. Malhotra, "In-Place Concrete Strength: New Pullout Methods," ACI Journal, Vol 76, (1979), pp 1267-1282.

Measurements on Steel in Concrete

The electrical potential method is commonly used to assess the corrosion condition of steel reinforcement in concrete. The electrical potentials of steel reinforcement are measured by making an electrical connection from a voltmeter to the reinforcement, and a second electrical connection from the voltmeter to a reference cell in physical contact with the surface of the concrete (Figure 3). Dry concrete must be moistened before electrical measurements are made. A saturated copper-copper sulfate electrode is commonly used as the reference cell. The electrical potential of the reinforcement below the reference cell is measured.

If the electrical potential of the steel reinforcement is more negative than -0.35 volts versus the copper sulfate electrode, active corrosion is probably taking place. Values in the range of -0.30 to -0.35 volts seem to suggest that corrosive conditions are developing within the concrete, while values less negative than -0.30 volts indicate that the steel is probably passive -- i.e., not corroding.[7]

An electrical potential diagram of a concrete slab can be constructed in which areas of similar potentials are outlined. This diagram can be used to identify areas where the reinforcement may be corroding.

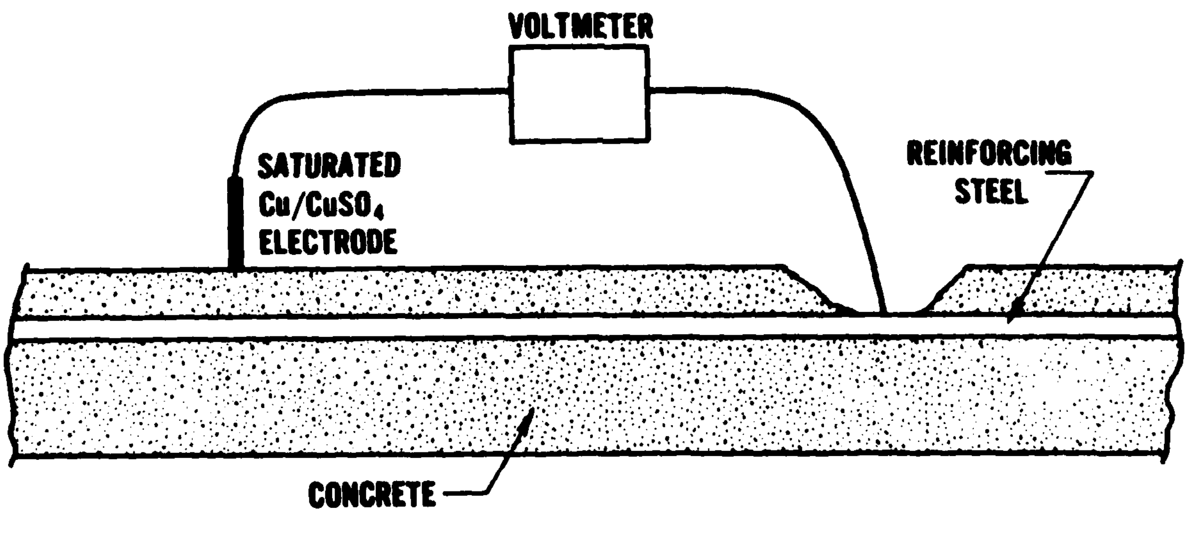

Figure 3. Measurement of electrical potential of steel reinforcing bars in concrete.

[7] K. C. Clear and R. E. Hay, Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, Vol 1; Effects of Mix Design and Construction Parameters, Federal Highway Administration Report No. FHWA-RD073-32 (1973).

Advantages

The equipment is inexpensive, and only a moderate amount of skill is needed to make the measurements. Measurements of the electrical potential of steel reinforcement provide information concerning the probability of corrosion.

Limitation

Information on either the rate or the extent of corrosion is not obtained. In addition, a direct electrical connection must be made to the reinforcing steel. If the steel is not exposed, then some concrete covering must be removed.

Electromagnetic Methods

The presence of flaws or changes in composition of metals will affect their electrical and magnetic properties. Therefore, it is possible to infer the presence of anomalies by making measurements which rely on the electrical and magnetic properties of metals. The following NDE methods can be used: eddy current testing, magneto-inductive testing, and magnetic particle testing.

Eddy Current Inspection

Eddy current inspection is a versatile NDE method based on the principles of electromagnetic induction; it is only applicable to inspection of metals.[8]

Description of Method. A coil carrying an alternating electric current will have an associated alternating magnetic field which acts to oppose the flow of current into the coil (Figure 4). When the coil is brought near a conductive material, the alternating magnetic field will induce in the material a closed-loop current flow known as eddy current. The eddy currents will also be alternating, and, therefore, a secondary magnetic field is associated with them. The secondary magnetic field will oppose the magnetic field of the coil. When the energized coil is brought near a metal surface, there will be a change in the current flow in the coil. Measuring the changes in the current flow (or the coil impedance) is the basis of eddy current inspection.

The magnitude of the change in the coil current will depend on the intensity of the eddy currents induced in the metal. Factors which influence the intensity of eddy current flow include:

1. the frequency and magnitude of the coil current
2. the electrical conductivity of the metal
3. the magnetic permeability of the metal
4. the size and shape of the test object
5. the proximity of the coil to the test object

[8] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

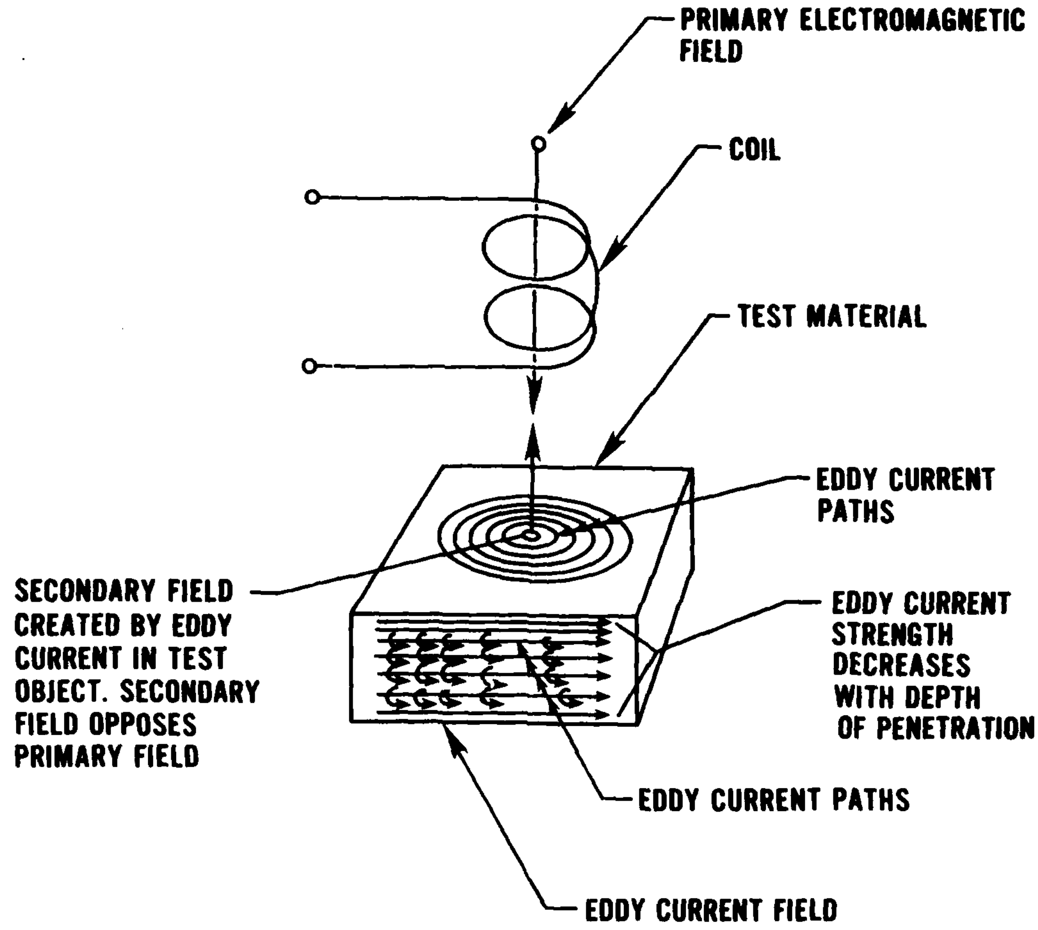

Figure 4. Establishment of eddy currents in a metallic building material.

6. the presence of discontinuities or inhomogeneities in the metal.[9]

The electrical and magnetic properties of the metal are controlled by alloy composition, microstructure, and residual stress.[10]

Eddy Current Inspection Systems. The principal elements of an eddy current inspection system include the inspection coil, an oscillator to provide coil excitation, a detector to monitor changes in coil impedance, and an output device to display the test results. Various coil geometries are available, depending on the specific application. An important principle when inspecting the discontinuities is that the maximum signal is obtained when the

[9] W. J. McGonnagle, Nondestructive Testing (Gordon and Breach, 1969).
[10] Metals Handbook, Vol II, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

eddy current flow is transverse to the flaw. Thus, the user needs to understand the relationships between coil configuration, eddy current flow and type of flaw to be detected.

The frequency of the excitation current affects the depth of the eddy currents and the sensitivity of flaw detection. The coil frequency can be increased to detect small, near-surface flaws: penetration is reduced, but sensitivity is increased. If sub-surface flaws are to be detected, a lower frequency should be used; however, the minimum size of flaws that can be detected is increased. Thus, there is a trade-off between penetrating ability and sensitivity; this is also common to other inspection methods. The range of frequencies is from 200 Hz to 6 MHz, with the lower frequencies used primarily for inspecting ferromagnetic metals.[11]

The detector circuit can also take many forms, depending on the application of the instrument. In any case, the changes in coil impedance that occur during inspection are small; bridge circuitry, similar to that used to monitor electrical resistance strain gages, is used to detect these changes. In making a measurement, the impedance bridge is first balanced by using an internal adjustment or placing the coil on a reference object of acceptable quality; then the coil is placed on the test object. Any difference between test object and reference object will result in an imbalance of the bridge which is indicated on the output device. There are many output devices: audible alarms, meters, X-Y plotters, strip-chart recorders, magnetic tape, storage oscilloscopes, or a computer.

Instrument Calibration. Because many factors may affect the coil impedance when a test is performed, the object used to calibrate the instrument must be carefully chosen. For example, to detect cracks, the reference object must have the same electrical and magnetic properties as the test object; otherwise, differences in alloy composition could be interpreted as a crack. Therefore, a user must be knowledgeable about operating an eddy current device in order to calibrate it properly and to interpret test results.

Applications. Eddy current inspection has many uses, including the detection of flaws such as cracks, porosity, or inclusions in metals; detection of changes in alloy composition or microstructure; and the measurement of the thickness of nonconductive coatings on a metal.

Limitations. One important limitation to eddy current inspection is the volume of material examined. The inspection depth depends on the penetration depth of eddy currents, the intensity of which decreases exponentially with depth. The strength of the signal due to a particular defect will depend on the nearness of the coil to the surface of the test object. As this distance increases, called "lift-off," the signal strength diminishes. The lift-off effect is so strong that it may mask signal changes due to defects. Therefore, care must be taken to ensure uniform contact between coil and test object; it may be difficult to test objects with rough or irregular surfaces. The "lift-off" effect may be used to measure the thickness of nonconductive coatings on conductive metals, or non-magnetic metal coatings on magnetic

[11]Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

metals. Proper calibration samples are required in order to use an eddy current instrument as a thickness gage.

Magneto-Inductive Methods

This technique is only applicable to ferromagnetic metals and is primarily used to distinguish between steels of different alloy composition and different heat treatments. The principle involved is electromagnetic induction. The equipment circuitry resembles a simple transformer in which the test object acts as the core.[12] There is a primary coil connected to a power supply delivering a low frequency (10 to 50 Hz) alternating current, and a secondary coil feeding into an amplifier circuit. In the absence of a test object, the primary coil induces a small voltage in the secondary coil, but when a ferromagnetic object is introduced, a much higher secondary voltage is induced. The nature of the induced signal in the secondary coil is a function of the magnetization characteristics of the object. Changes in these characteristics are used to distinguish between samples of different properties. As in the case of eddy current inspection, this method can only be used for quantitative measurement if proper calibration is performed.

Cover Meters

Cover meters are portable, battery-operated magnetic devices that are primarily used to estimate the depth that reinforcing steel (bars and tendons) is embedded in concrete, and to locate its position. In addition, some information can be obtained regarding the dimensions of the reinforcement.[13]

Principle and Applications. Cover meters are magnetic devices based on the magneto-inductive principle. A typical meter is shown in Figure 5. A magnetic field is induced between the two faces of the probe (which houses a magnetic core) by an alternating current passing through a coil. If the magnetic field passes through concrete containing reinforcement, the induced secondary current is controlled by the reinforcement. The magnitude of this change in inductance is measured by a meter. For a given probe, the magnitude of the induced current is largely controlled by the distance between the steel reinforcement and the probe.

The relationship between the induced current and the distance from probe to the reinforcement is nonlinear, largely because the magnetic flux intensity of a magnetic material decreases with the square of the distance. In addition, the magnetic permeability of the concrete, even though it is low, will have some effect on the reading. Therefore, the calibrated scales on the meters of commercial equipment are nonlinear. Also, a meter must be readjusted if a different probe is attached.

The probe is highly directional -- i.e., a sharp maximum in induced current is observed when the long axis of the probe and reinforcement are aligned, and when the probe is directly above the reinforcement.

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[12]Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

[13]V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, ACI Monograph No. 9 (1976).

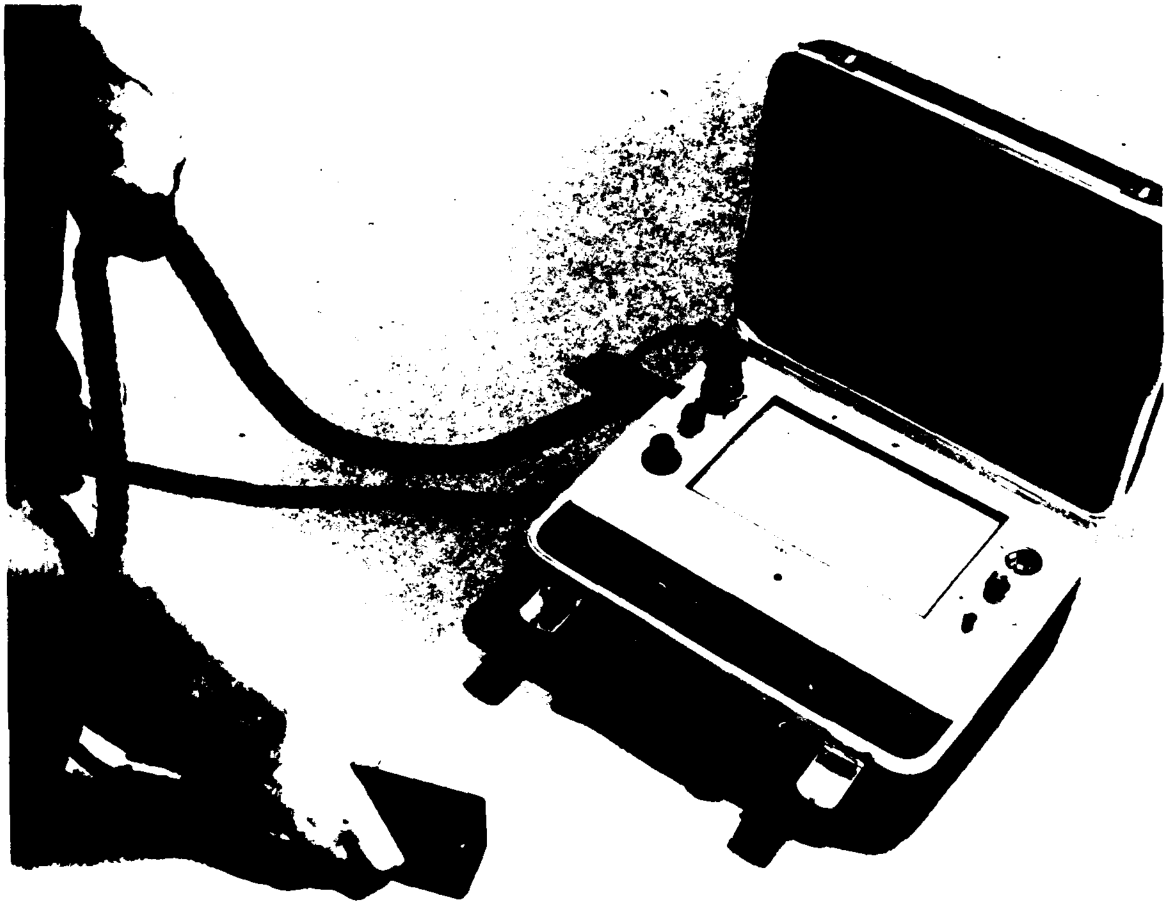

Figure 5. Cover meter used to detect steel reinforcement.

The commercial cover meter shown in Figure 5 can measure concrete cover over reinforcement up to 8 in. (200 mm). By using spacers of known thickness, the size of reinforcing between 3/8 and 2 in. (6 to 51 mm) can be estimated.

Another possible application of the cover meter is to estimate the thickness of slabs which are accessible from both sides. If a steel plate is aligned on one side with the probe on the other side, the measured induced current will indicate the thickness of the slab. For this application, a series of calibration tests must be performed first.

Advantages. Cover meters are portable, inexpensive instruments that can be easily used. They are most useful when reinforced concrete has only one layer of widely separated reinforcing bars.

Limitations. In highly reinforced concrete, the presence of secondary reinforcement makes it difficult to determine satis torily the depth of concrete cover. Furthermore, reinforcing bars running parallel to that being

measured influence the induced current if the distance between bars is less than two or three times the cover distance.[14]

Magnetic Particle Inspection

Principle of Method. This inspection method relies on the tendency of cracks to alter the flow of a magnetic field within a metal so that fine magnetic powder will be attracted to the crack zone, allowing cracks to be identified.[15] For example, consider a bar magnet in which the magnetic field flows through the magnet from south to north poles. If ferromagnetic particles are sprinkled over the middle surface of a crack-free magnet, there will be no attraction because the magnetic field lies wholly within the magnet. Now consider a cracked magnet; the two sides of the crack act as north and south poles, and the magnetic field bridges the gap. However, some of the magnetic field will leak out of the magnet into the air, and ferromagnetic powder would be attracted by the leakage field. Therefore, the attraction of the powder indicates a crack. A small crack and a subsurface crack would also produce a leakage field, but the response would be weaker for the subsurface crack.

Application of Method. In using the magnet particle method, it is necessary to magnetize the object being inspected, apply ferromagnetic particles, and then inspect for cracks. Two general types of magnetic fields may be induced in the test object: circular and longitudinal. A circular field is produced by passing an electric current through the test object: the magnetic field then would be concentric with the direction of current flow. A longitudinal field could be created by placing the test object inside a coil carrying electric current: the magnetic field then would be parallel to the longitudinal axis of the coil. The direction of the magnetic field relative to the test object controls which cracks will be detected. Strong leakage fields are produced by cracks which intersect the magnetic lines of force at an angle; no leakage fields are produced by cracks parallel to the magnetic lines of force. Therefore, complete inspection should include rotation of the test object with respect to the magnetic field to make sure that all existing cracks intersect the magnetic field lines.

In field inspections, it usually is not practical to pass a current through the entire part or surround the part with a coil. Portable units are available that permit inspection of small portions of the test object at one time. For example, prods can introduce a flow of current between two contact points on the object. In this case, a circular magnetic field is induced. A yoke -- a U-shaped electromagnet in which the poles are brought into contact with the test object -- can also be used. With a yoke, a longitudinal magnetic field is set up in the object, and the lines of force in the electomagnet run from one pole to the other. With either portable method, only a small

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[14] V. M. Malhotra, Testing Hardened Concrete: Nondestructive Method, ACI Monograph No. 9 (1976).

[15] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976); F. W. Dunn, "Magnetic Particle Inspection Fundamentals," Lesson 3, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); C. E. Betz, "Magnetic Particle Inspection Applications," Lesson 4, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977).

portion of a large test object can be inspected at one time; 12 in. (300 mm) is a practical limit for spacing between prod contacts.[16]

The choice of current used to magnetize the test object is important. If subsurface cracks are to be detected, direct current must be used because alternating current will only produce a surface magnetic field. The direct current may be from a constant or pulsating source, though the pulsating type is preferred because it imparts greater mobility to the ferromagnetic powder. The current supply is low voltage and very high amperage for user safety, but still permits strong magnetization of the test object. Inspection is usually carried out with the current on, but if the metal has high retentivity (permanent magnetism), the current may be turned off before the powder is applied.

The powder used to indicate the leakage fields may be dry or suspended in a liquid. Dry powders are preferred for the best sensitivity to subsurface cracks and should be used with direct current. Wet powders are superior for detecting very fine surface cracks. To improve visibility, powders are available in various colors, providing high contrast with the background. In addition, fluorescent particles are available for increased visibility.

Advantages. The magnetic particle inspection method has several advantages over other crack detection systems.[17] The equipment is portable, inexpensive, and simple to operate; positive crack indications are produced directly on the part and no electronic equipment is needed. Any part that is accessible can be inspected.

Limitations. However, there are some limitations that the user must understand. The method will only work with ferromagnetic metals. For complete inspection, each area needs to be inspected more than once using different magnetic field directions; very large currents are needed to impact large areas at once. Experience and skill are needed to interpret properly the particle indications and to recognize patterns which do not indicate cracks. Demagnetization may be required after inspecting steels with high magnetic retentivity. The maximum depth of the flaw detection is about 0.5 in. (13 mm), and the detectable flaw size increases as flow depth increases.

Leak Testing Method

Principle of Method

Leak testing is the detection of holes in pipes and tanks which permit the escape of liquids or gases.[18] There are many different methods of leak testing, but they can be generally classified into two categories. In the first, the leaking system is monitored under normal operating conditions. This includes the use of pressure meters, the application of a soap solution, or the use of audio or amplified listening devices. In the second category, a

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[16] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

[17] Metals Handbook, Vol 11.

[18] G. W. Sevall, Nondestructive Testing of Construction Materials and Operations, Technical Report M-67/AD774847 (U.S. Army Construction Engineering Research Laboratory, [CERL], 1973).

particular substance is added into the system flow to provide special indications of leakage. This includes additives such as colored dyes, Freon 12 and helium gas, radioactive tracers, and odorous indicators.

Applications

Many leak detection methods are suitable for field application. Liquid storage vessels and aboveground piping can usually be checked visually for leakage under normal operating conditions with no special equipment. Gas-carrying systems usually can be checked best in the field with a soap solution or (with freon gas added to the system) a propane torch. These systems have no special power requirements, and none of the equipment involved weighs more than 5 lb (2 kg).

Advantages

Leak detection methods can locate flaws too small to be found by any other NDE technique. Leaks with rates as small as 10^{-12} cc/sec can be detected with radioactive tracers and radiation monitoring devices, while a soapy water solution can locate leaks with rates as low as 10^{-3} cc/sec.[19]

Limitations

Flaws can be detected only if they penetrate through a structure that can be held at pressure conditions differing from those of the surrounding atmosphere.

Maturity Concept

Principle and Application of Method

The maturity concept has been proposed as a method for predicting early age strength development of hardening concrete. It relates the combined effect of temperature and hydration time of concrete to its strength.[20] Maturity (M) is usually expressed as:

$$M = \sum (T-T_0)\Delta t \qquad [\text{Eq } 1]$$

where: T = temperature of the concrete

T_0 = the highest temperature below which the strength of hardening concrete does not change

Δt = the increment of time for each temperature.

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[19] G. W. Sevall, Nondestructive Testing of Construction Materials and Operations, Technical Report M-67/ADA774847 (CERL, 1973).

[20] A. G. A. Saul, "Principles Underlying the Steam Curing of Concrete," Magazine of Concrete Research, Vol 1, No. 2 (January 1949), pp 21-28.

According to the maturity concept, the strength of a given concrete mix is a single-valued function of maturity, independent of the actual temperature history.[21]

To apply this method, one first experimentally determines the strength-maturity relation of the concrete mix to be used in building the structure. This is done by making and curing standard specimens in a laboratory, monitoring the actual concrete temperature, and testing strength at various ages. From the temperature record, the corresponding maturity value at each test age is calculated, and strength versus maturity data are generated. Various equations for the strength-maturity relation have been proposed, and can be used in analysis of the data.[22] During construction, the in-place concrete temperature is recorded, from which maturity values at any age can be determined. The previously determined strength-maturity calibration curve is used to predict the strength of the in-place concrete.

Maturity can be calculated using temperature records from continuous strip-chart recorders or from digital data-loggers, which print out the temperature at regular time intervals. As an alternative, commercial "maturity meters" are available; these monitor the in-place temperature and automatically compute the cumulative maturity. Such instruments cost about $3000. Recently, multi-channel maturity meters have been developed to allow monitoring maturity at many locations with a single instrument. In addition, single-use, disposable meters have been produced, although their reliability has not been tested. Finally, one may use programmable data-loggers as maturity meters.

Advantage

Because in-place temperatures are measured, the maturity method accounts for one of the major factors affecting early-age strength development of concrete.

Limitations

Since only temperature is measured, another method is needed to verify that the in-place concrete has the correct mix proportions. Otherwise, the user has no way of knowing if his/her strength-maturity calibration curve is appropriate. Accelerated curing tests of samples taken from the concrete batch, or other in-place tests discussed in this report may be used. Because of the nonuniform temperature distribution in the structure, the temperature probes must be carefully located to avoid overestimating maturity development in the critical strength regions. In addition, there is a question about whether Eq 1 is the best temperature-time function for computing maturity.

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[21] A. G. A. Saul, "Principles Underlying the Steam Curing of Concrete," Magazine of Concrete Research, Vol 1, No. 2 (January 1949), pp 21-28.

[22] J. M. Plowman, "Maturity and the Strength of Concrete Research," Magazine of Concrete Research, Vol 8, No. 22 (1956), p 13; H. S. Lew and T. W. Reichard, Prediction of Strength of Concrete from Maturity in Accelerated Strength Testing, SP 56 (ACI, 1978); N. J. Carino, Temperature Effects on the Strength-Maturity Relations of Mortar, NBSIR 81-2244 (National Bureau of Standards, October 1980).

Carino discusses this problem and suggests alternative methods.[23] Finally, the maturity method is only applicable for strength prediction in new construction and cannot be used to estimate the strength of concrete in existing structures.

Microwave Inspection

Microwaves (or radar waves) are a form of electromagnetic radiation which have frequencies between 300 MHz and 300 GHz corresponding to wavelengths of 1 m to 1 mm. Microwaves are generated in special vacuum tubes called klystrons and transported in a circuit by waveguides. Diodes are commonly used to detect microwaves.

Applications

The use of microwaves to estimate the moisture contents of roofing materials and concrete has been explored.[24] Similar to capacitance instruments (see p 43), the effect of water on the dielectric properties of materials is determined. Boot and Watson report that the microwave technique only estimates the moisture content of concrete to within 12 to 30 percent of its mean value.[25] The low accuracy of microwave inspection is largely attributed to the heterogeneity of concrete, and the internal scattering and diffraction it causes.

Limitations

The feasibility of using microwaves for inspecting installed construction materials has not been demonstrated. Further development work is required if the microwave method is to become a reliable field NDE method.

Moisture Detection Methods

Many of the problems encountered in a building are caused by moisture. Visual inspection can reveal surface moisture, but even if a surface is dry,

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[23] N. J. Carino, Temperature Effects on the Strength-Maturity Relations of Mortar, NBSIR 81-2244 (National Bureau of Standards, October 1980).

[24] H. Busching, R. Mathey, W. Rossiter, and W. Cullen, Effects of Moisture in Built-up Roofing -- A State-of-the-Art Literature Survey, National Bureau of Standards Technical Note 965 (1978); V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, ACI Monograph No. 9 (1976).

[25] A. Boot and A. Watson, Applications of Centimetric Radiowaves in Nondestructive Testing, in Application of Advanced and Nuclear Physics to Testing Materials, ASTM STP-373 (1965), pp 3-24.

subsurface moisture can be present. Four NDE methods are often used for moisture inspection -- measurements with electrical resistance probes, capacitance instruments, nuclear meters, and infrared thermography.[26]

Electrical Resistance Probe

Principle and Applications. The resistance probe method involves measuring the electrical resistance of a material, which decreases as the moisture content increases. Most instruments consist of two closely spaced probes and a meter-battery assembly which are enclosed in one housing or in two attached assemblies. A commercial instrument is shown in Figure 6. The probes are usually insulated except at the tips so that the region being measured lies between the tips of the probes. The probe can penetrate soft materials, such

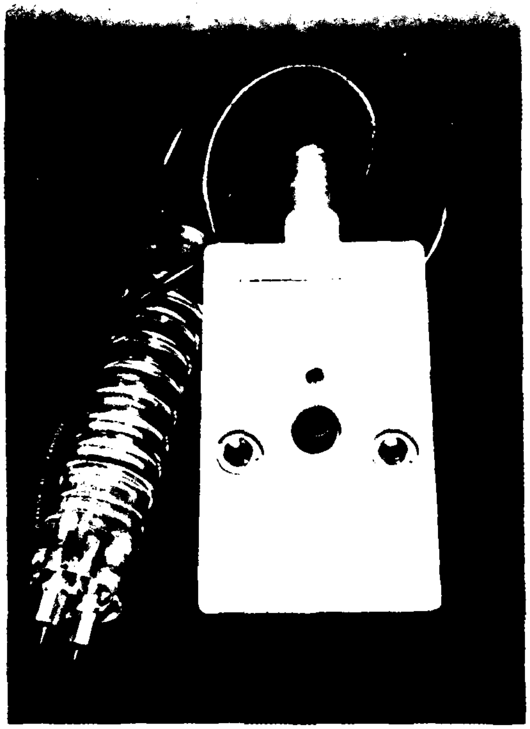

Figure 6. Electrical resistance instrument for detecting moisture.

[26] H. Busching, R. Mathey, W. Rossiter, and W. Cullen, Effects of Moisture in Built-up Roofing -- A State-of-the-Art Literature Survey, National Bureau of Standards Technical Note 965 (1978); D. R. Jenkins, L. J. Knab, and R. G. Mathey, Moisture Detection in Roofing by Nondestructive Means, A State-of-the-Art Survey, National Bureau of Standards Technical Note (In Press); L. Knab, R. Mathey, and D. Jenkins, Laboratory Evaluation of Nondestructive Methods to Measure Moisture in Built-Up Roofing Systems, National Bureau of Standards Building Science Series 131 (1981).

as roofing membranes, so that moisture at various distances below the surface can be detected. Operation of a resistance probe is very simple. A voltage is impressed between the probes and the resistance measured.

Probe instruments have been used for moisture detection in plaster, brick, concrete and roofing materials. Similar procedures have been used for determining the electrical resistance of soils, except a four probe system is used.

Calibration. The electrical resistance probe and other moisture measuring instruments are usually calibrated by obtaining relationships between their response and the moisture content of materials similar to those being inspected. The moisture contents of the specimens are gravimetrically determined -- i.e., specimens are weighted before and after oven drying with the differences in weight giving their moisture contents.

Advantages. The simple, inexpensive instruments, while giving only a qualitative indication of wetness, are useful in identifying wet areas and for determining moisture migration patterns. More sophisticated instruments appear to be capable of giving semi-quantitative information if they are properly calibrated.

Limitations. Electrical resistance probe instruments do not determine moisture contents precisely.

Capacitance Instruments

Principle and Applications. Capacitance instruments used to detect moisture are based on the principle that moisture can affect the dielectric properties of a material.[27] The dielectric constant, K, of a material is a relative measure of the ability of a material to store electrical energy and is given by:

$$K = C/Co \qquad [Eq\ 2]$$

where C is the capacitance of a material and Co is the capacitance of a vacuum.

The dielectric constants for many dry building materials are usually low; e.g., for dry roofing materials, K ranges from 1 to 5, while water has a K of approximately 80.[28] The value of K for a moist material will theoretically increase linearly as the volume fraction of water increases. Capacitance-radio frequency instruments have been used to measure the moisture contents of paper products, wallboard, and roofing materials. Commercial capacitance instruments have various electrode configurations. The electrodes are

[27] D. R. Jenkins, L. J. Knab, and R. G. Mathey, Moisture Detection in Roofing by Nondestructive Means, A State-of-the-Art Survey, National Bureau of Standards Technical Note (In Press).
[28] Jenkins et al., Moisture Detection.

attached to a constant frequency alternating current source and establish an electrical field in the material to be tested. Current flow or power loss -- indicating moisture content -- is then measured. Most instruments operate in the radio frequency region (1 to 30 MHz).

Advantages. Capacitance instruments are portable and measurements can be taken rapidly.

Limitations. A recent investigation by Knab et al. suggests that capacitance instruments may not give reliable quantitative measurements of the moisture contents of roofing systems.[29] Apparently, further work is needed to establish the reliability of this method for moisture measurements of building materials.

Nuclear Meter

Principle of Method. Fast neutrons, emitted during the decay of radioactive isotopes, are used in making moisture content measurements.[30] Fast neutrons from the isotope source enter the material and are both scattered and slowed by collisions with the nuclei of the atoms composing the material (Figure 7). Nuclei of all materials slow down the neutrons by momentum exchange, but the speed reduction is greatest for collisions with hydrogen nuclei, which have about the same mass as the neutrons. Some of the slow or thermal

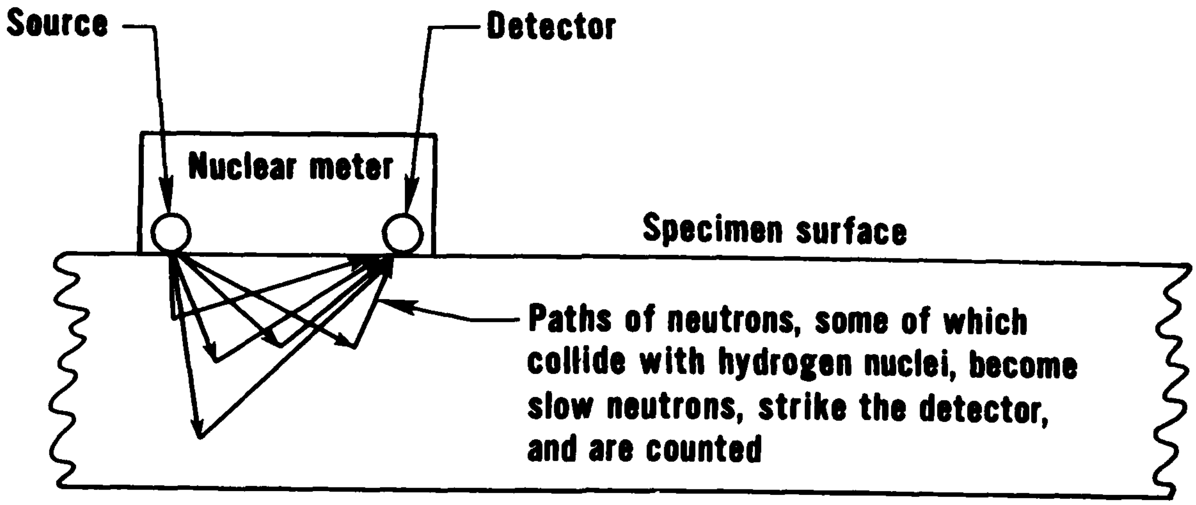

Figure 7. Process by which a nuclear meter detects moisture.

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[29] L. Knab, R. Mathey, and D. Jenkins, Laboratory Evaluation of Nondestructive Methods to Measure Moisture in Built-Up Roofing Systems, National Bureau of Standards Building Science Series 131 (1981).

[30] A. Boot and A. Watson, Applications of Centimetric Radiowaves in Nondestructive Testing, in Application of Advanced and Nuclear Physics to Testing Materials, ASTM STP-373 (1965), pp 3-24; D. R. Jenkins, L. J. Knab, and R. G. Mathey, Moisture Detection in Roofing by Nondestructive Means, A State-of-the-Art Survey, National Bureau of Standards Technical Note (In Press).

neutrons are scattered so that they reach the slow neutron detector in the instrument and are counted for a specified period of time. The thermal neutrons reaching the detector are much more likely to have collided with hydrogen nuclei than with other atomic nuclei because the scattering cross-section of hydrogen is greater than for other atoms likely to be present. The detector measures primarily the backscattering of slow neutrons which have collided with hydrogen nuclei in the surface region of materials. For example, the depth of measurement is limited to 2 to 8 in. (51 to 203 mm) in soils.

Commercial Meters and Applications. Nuclear meters (Figure 8) are used to measure both moisture content and density of soils, portland-cement concrete, asphaltic concrete, and roofing materials.[31] These meters consist of a shielded radioactive isotope source, a detector or counting device, and readout equipment. In commercial meters, the isotopes used are radium

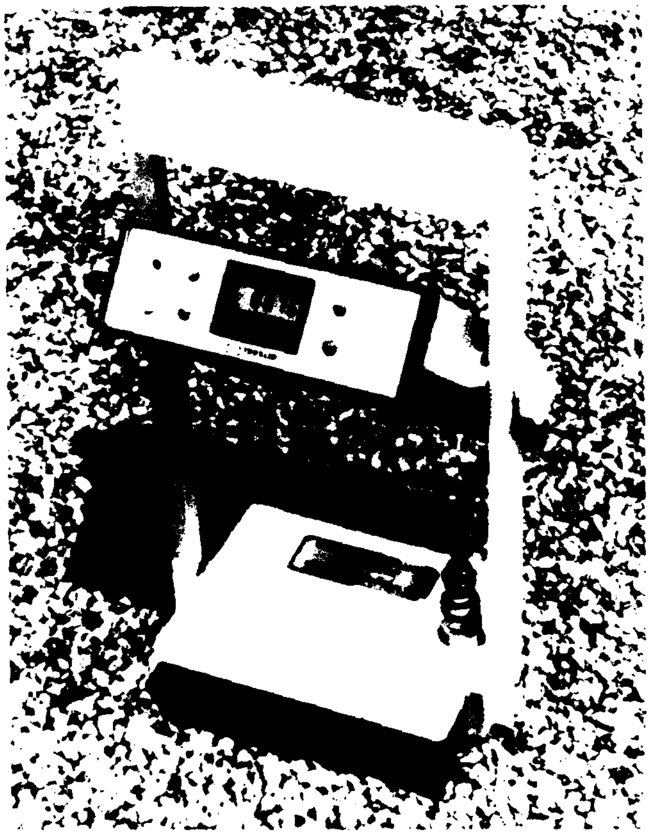

Figure 8. Nuclear meter used to measure moisture content of materials.

[31] V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, ACI Monograph No. 9 (1976); H. Busching, R. Mathey, W. Rossiter, and W. Cullen, Effects of Moisture in Built-up Roofing -- A State-of-the-Art Literature Survey, National Bureau of Standards Technical Note 965 (1978).

226-beryllium, and americium 241-beryllium. Both americium and radium are alpha particle emitters. These particles interact with the nucleus of beryllium, resulting in the emittance of fast neutrons.

In addition to neutron sources, most commercial nuclear moisture meters also have gamma ray sources. The gamma rays are used to determine the density of materials. See p 55 for an explanation of the principle.

Advantages. Nuclear meters are portable, and moisture measurements can rapidly be made on materials.

Limitations. The hydrogen atoms of building materials in addition to those of water will contribute to the number of detected thermal neutrons. For example, asphalt in a roofing membrane may contribute to a reading because it contains bonded hydrogen atoms. For hydrogen-containing materials, the meter must be calibrated with samples identical to those expected during field inspection. Also, a license must be obtained from the Nuclear Regulatory Commission to use the radioactive isotopes in the neutron source of the neutron moisture meters.

Infrared Thermography

In addition to locating heat loss, infrared thermography can be used to detect moisture in building materials if heat is flowing through them. The presence of moisture will affect the heat transfer properties of materials; this permits the identification of wet areas by thermography. The principles involved in making thermography scans are discussed under Radiography. This method is being used in making aerial scans of roofs: large roof areas and many buildings can be scanned in a relatively short time.[32] Handheld infrared cameras also are being used to measure heat losses and to detect moisture in roofing systems.[33] See Thermal Inspection Methods for additional applications of infrared thermography. In using thermography to detect moisture in roof systems, it is necessary to assume that temperature gradients are caused by moisture and are not associated with differences in roofing composition or thickness. Because construction and thickness variations can be present, results from thermographic inspections should be interpreted carefully.

Paint Inspection Gage (Tooke Gage)

Principles and Applications

The paint inspection gage measures dry paint film thickness by the microscopic observation of a small v-groove cut into the paint film. In addition, the number of paint layers and their individual thicknesses can be determined. The thickness of dry coating applied to any type of surface can be measured -- e.g., to wood, metal, glass, or plastic. A commercially

[32] H. Busching, R. Mathey, W. Rossiter, and W. Cullen, Effects of Moisture in Built-up Roofing -- A State-of-the-Art Literature Survey, National Bureau of Standards Technical Note 965 (1978).

[33] W. Tobiasson and C. Korhonen, Summary of Corps of Engineering Research on Roof Moisture Detection and the Thermal Resistance of Wet Insulation, Special Report 78-29 (Cold Regions Research and Engineering Laboratory, 1978).

available paint inspection gage, the Tooke Gage, is shown in Figure 9. This gage is easily portable, with overall dimensions of 4.5 x 3.5 x 1 in. (114 x 89 x 25 mm); it weighs 26 oz (0.7 kg). Three cutting tips are furnished; these permit measurements of film thicknesses up to 50 mil (0.13 mm).

Limitation

A disadvantage of this method is that a cut is made in the paint film which may have to be repaired, depending on the substrate and the severity of the environment.

Figure 9. Tooke Gage for measuring the thicknesses and number of paint layers.

Pin Hole Detector

Principle and Application

A pin hole or holiday detector is used to find pin holes (holidays) in nonconductive coatings applied to metals. Most commercial instruments consist of a probe or electrode, which makes contact with the coating through a moist sponge, and an earth lead, such as an alligator clip (Figure 10), which is attached to an area of bare metal. When the moist sponge passes over a pin hole, an electrical circuit is completed, and an alarm sounds. Most detectors use a direct current power source in the range of 9 to 67.5 volts.

Figure 10. Device to inspect nonconductive coatings on metals for pin holes.

Limitations

There are several problems in using such a detector to inspect for pin holes. If a metallic object is completely coated, part of the coating must be removed so that the earth lead can make contact with the metal. Pin holes can be induced in weakened areas of a coating if high voltage (10 kV) detection is used. The results are quantitative since no information on the size of a pin hole is given.

Proof Load Testing

Principle of Method

Proof load testing is based on the concept that a structure capable of surviving the stresses of a severe overloading should be serviceable under normal operating conditions.[34] Proof loading requires overloading a structure in a load pattern similar to operating conditions (e.g., high pressure in a pipeline).

Applications

Proof load testing can be used with leak testing (see Electromagnetic Methods, [p 32]) in pressure vessels and pipeline inspection to increase the sensitivity of leak detection. This method is generally used as a last resort to determine the adequacy of a structural system.

Advantage

An entire structure can be tested in its "as-built" condition.

Limitations

The test may either cause the premature failure or the destruction of a structure. Proof load testing requires extensive planning and preparation, and is usually expensive.

Probe Penetration Method

Principle of Method

The probe penetration method includes measuring the exposed length of a cylindrical steel probe driven into concrete by a powder charge. This method is useful for assessing the quality and uniformity of concrete in situ, and for delineating areas of poor quality or deteriorated concrete in structures.

Probe penetration results have also been used to estimate the compressive strength of concrete by using correlation graphs. The graphs are constructed

[34] G. W. Sevall, Nondestructive Testing of Construction Materials and Operations, Technical Report M-67/AD774847 (CERL, 1973).

by plotting the exposed lengths of probes versus experimentally measured compressive strengths. This can be done by performing penetration tests on a concrete slab and taking core samples for compression testing.

Probe Equipment and Its Use

The Windsor Probe is the most commonly selected, and possibly the only, commercially available apparatus for measuring the penetration resistance of concrete. It consists of a special driving gun (Figure 11) which uses a 32 caliber blank with a precise quantity of powder to fire a high-strength steel probe into the concrete. A series of three measurements is made in each area using the spacer plate shown in Figure 12. The length of a probe extending from the surface of the concrete can be measured with a simple device, as shown in Figure 13.

Operating procedures for the Windsor Probe are given by the manufacturer. In addition, testing procedures are given in ASTM Standard C 803.[35] The probe can be easily operated by concrete inspectors, and is readily portable.

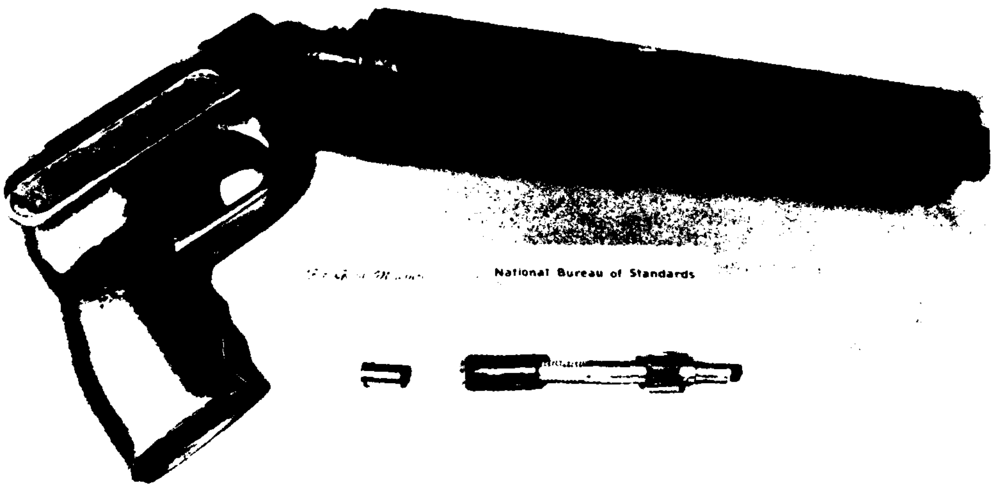

Figure 11. Windsor probe apparatus showing the gun, probe, and blank cartridge.

[35]Test for Penetration Resistance of Hardened Concrete, ASTM C 803 (1979).

Figure 12. Windsor probe in use.

The manufacturer supplies a set of five calibration curves, each corresponding to a specific Moh's hardness for the coarse aggregate used in the concrete. With these curves, probe measurements can be converted to compressive strength values. However, Arni observes that use of the manufacturer's calibration curves often results in grossly incorrect estimates of the compressive strength of concretes.[36] Therefore, the Windsor Probe should be calibrated by the individual user, and should be recalibrated whenever the type of aggregate or mix design is changed.

[36]H. T. Arni, Impact and Penetration Resistance Tests of Portland Cement Concrete, Federal Highway Administration Report No. FHWA-RD-73-5 (1972).

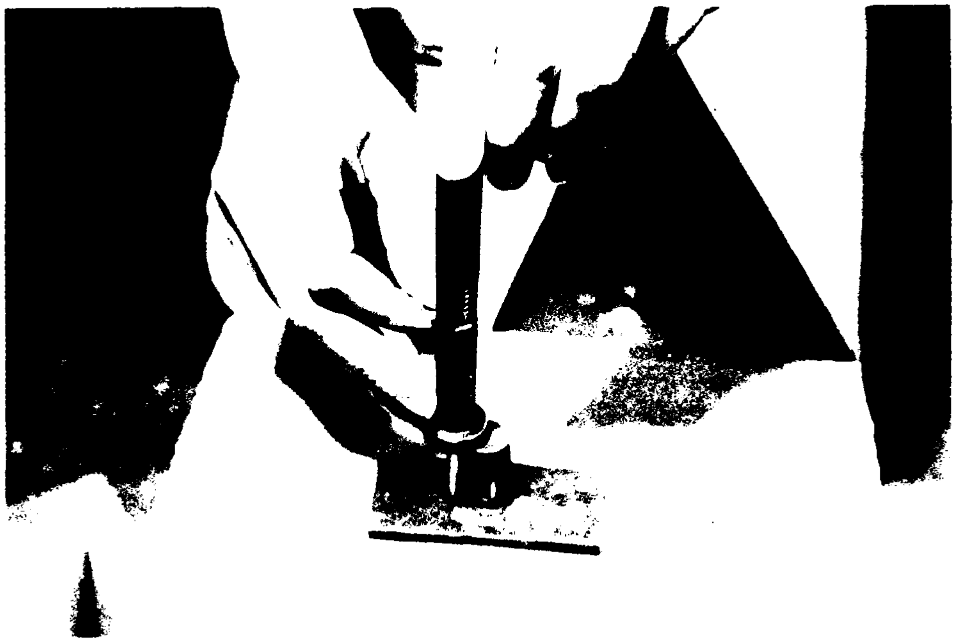

Figure 13. Device for measuring length of probe extending from surface of concrete.

The Windsor Probe can be used for assessing the quality and uniformity of concrete because physical differences in a concrete will affect its resistance to penetration. A probe will penetrate deeper as the density, subsurface hardness, and strength of the concrete decrease. Areas of poor concrete can be delineated by making a series of penetration tests at regularly spaced locations.

The Windsor Probe has been used to estimate the compressive strength of concrete. However, the relationship between the depth of penetration of the probe and the compressive strength can only be obtained empirically because the penetration of the probe depends on a complex mixture of tensile, shear, frictional, and compressive forces.[37] The estimation of compressive strengths with the Windsor Probe, therefore, must be made using a correlation diagram with appropriate confidence limits.

The probe technique appears to be gaining acceptance as a practical NDE method for estimating the compressive strength of concrete. Improved correlations between probe results and in-place strength can be obtained by keeping the curing conditions of the test specimens close to those expected for in-place concrete, and by making sure that the test concrete is representative of the in-place concrete. If the Windsor Probe is calibrated using concrete

[37]H. T. Arni, Impact and Penetration Resistance Tests of Portland Cement Concrete, Federal Highway Administration Report No. FHWA-RD-83-5 (1972).

specimens taken from an early construction stage, the calibration chart could be used to estimate the strength of concrete placed during later stages (assuming that the concrete design is the same).

Advantages

The Windsor Probe equipment is simple, durable, requires little maintenance and can be used by inspectors in the field with little training. The probe test is very useful in assessing the general quality and relative strength of concrete in different parts of a structure.

Limitations

Care must be exercised, however, because a projectile is fired; safety glasses should be worn. (Note: The gun can only be fired when it is pushed against the spacer plate.) The Windsor Probe primarily measures surface and subsurface hardness; it does not yield precise measurements of the in situ strength of concrete. However, useful estimates of the compressive strength of concrete may be obtained if the probe is properly calibrated.

The Windsor Probe test does damage the concrete, leaving a hole of about 0.32 in. (8 mm) in diameter for the depth of the probe, and may cause minor cracking and some surface spalling. Minor repairs of exposed surfaces will be necessary.

Radiography

Radiography allows the internal structure of a test object to be inspected by penetrating radiation, which may be electromagnetic (X-ray, gamma rays, etc.) or particulate (neutrons).[38] The object is exposed to a radiation beam, and the intensity of the radiation passing through is reduced according to the object's variations in thickness, density, and absorption characteristics. The quantity of radiation passing through the object is measured and used to deduce internal structure. X-rays and gamma rays have been most widely used.

X-rays

X-rays are produced by bombarding a target material with fast moving, high energy electrons. The high energy electrons collide with electrons in the target, which are promoted to higher energy levels. As the promoted electrons return to their ordinary energy levels, their excess energy results in the emission of X-rays. X-rays are generated in an evacuated chamber (X-ray tube) in which high energy electrons are generated by applying a very high voltage between an incandescent filament (the electron source) and the target

[38] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976); J. K. Aman, G. M. Carney, D. McBride, and R. E. Turner, "Radiographic Fundamentals," Lession 8, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); D. McBride, G. Carney, R. Turner, and E. O. Lomerson, "Fundamentals of Radiography," Lesson 9, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977).

material. By varying the voltage, X-rays with different penetrating abilities can be generated. For example, 200 kV X-rays are capable of penetrating about 1 in. (25 mm) of steel, while 400 kV X-rays can penetrate up to 2 in. (51 mm) of steel,[39] which is about the maximum attainable with portable equipment. In general, the penetrating ability of X-rays of a given energy level decreases as the density of the object increases.

Gamma Rays

Gamma rays are physically indistinguishable from X-rays; the primary difference is the source. Gamma rays are the result of radioactive decay of unstable isotopes. Thus, there are some basic differences between gamma ray and X-ray radiography. Because gamma rays are produced by nuclear disintegrations, a gamma ray source will lose its intensity with time, so longer exposure times may be required for adequate inspection. In addition, each source produces rays of fixed penetrating ability. Isotopes of thulium, iridium, cesium, radium and cobalt have been used for radiography. Thulium has a penetrating ability of 0.5 in. (13 mm) of steel, while cobalt produces gamma rays capable of penetrating up to 9 in. (230 mm) of steel. The gamma sources usually used for inspecting concrete are given in Table 14. Note that the relative penetration abilities of the gamma rays are controlled by their energies.

Table 14

Gamma Ray Sources
(From J. K. Aman, G. M. Carney, D. McBride, and R. E. Turner, "Radiographic Fundamentals," Lesson 8, Fundamentals of Nondestructive Testing [Metals Engineering Institute, American Society for Metals, 1977].)

Radioactive Source	Gamma Energy (MeV)	Half-life ($t_{1/2}$)	Optimum Working Thickness of Concrete (mm)	Dose Rate*
Iridium 192	0.296 and 0.613	70 days	30-200	0.55
Cesium 137	0.66	33 years	100-300	0.39
Cobalt 60	1.17 and 1.33	5.3 years	150-450	1.35

*Roentgens per hour per curie at 1 m. One curie is equal to 3.7×10^{10} disintegrations per second.

[39] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

Portable gamma radiography units are available; these have greater penetrating capabilities than portable X-ray units. Therefore, gamma radiography is more commonly used for field inspections.

Principles and Applications

Gamma and X-ray radiation is attenuated (reduced) when passing through materials. The extent of attenuation depends on the density and thickness of the material, and on the energy of gamma rays. In radiography, differences in radiation attenuation produced by variations in the density and thickness of a material are recorded on photographic film. For example, when reinforced concrete is radiographically inspected, steel reinforcement attenuates the radiation more than concrete and appears as a lighter area in the film. Voids and cracks in the concrete appear as darker areas on the film because the incident radiation is attenuated little.

In practice, penetrating rays generated by a suitable source are allowed to pass through materials, with the emerging radiation being recorded on X-ray film held in a light-tight cassette. Some of the applications of gamma radiography are inspecting concrete to locate reinforcing bars, and to determine if excess microscopic porosity or macroscopic voids are present;[40] inspecting welds for cracks, voids, and slag inclusion; and inspecting masonry walls for the presence of reinforcement or grout.

Advantages

Radiography provides a method for readily characterizing the internal features of an in-place material or building component. This method is applicable to a variety of materials. Portable gamma radiography units can have greater penetrating abilities than portable X-ray units.

Limitations

The most important drawback of radiography is the health hazard associated with the penetrating radiation. A radiographic inspection program should be planned and carried out by trained individuals who are qualified to perform such inspection. All personnel involved in radiographic inspection must carry devices that monitor the radiation dosage to which they have been subjected, and must be protected so that the dosage rate does not exceed Federal limits. Gamma ray sources are inherently hazardous because they emit rays continuously, and high energy sources have extremely high penetrating ability. As a result, gamma ray sources require large amounts of shielding material; this limits the portability of gamma radiography equipment. The use of gamma-producing isotopes is closely controlled by the Nuclear Regulatory Commission; users must have a license.

[40] J. A. Forrester, "Gamma Radiography of Concrete," Proceedings of Symposium on Nondestructive Testing of Concrete and Timber, Session No. 2 (London: Institute of Civil Engineers, 1969), pp 9-13.

Seismic Testing

Principle of Method

Seismic testing is the evaluation of material integrity by analysis of shock wave transmission rates and effects.[41] An array of sensing devices around an explosive charge of known energy (the most common shock load input system) is used to record shock wave transmission rates. These rates can be related to material densities. Vibrational patterns induced from shock loading can be used to determine resonant frequencies in structures.

Applications

Seismic testing can measure soil densities and locate density variation boundaries (Figure 14). Soil density values can then be related to load bearing capacities and foundation preparation requirements. Seismic testing can also be used to check structures for possible resonant frequencies that could cause failure under operating dynamic loads.

Advantages

All components of a seismic test system are portable.

Limitations

Seismic testing is applicable only to monitoring soil conditions and structural vibrations. Multi-channel recording systems, power cables, and many sensing devices are needed. The hazards of explosives are also involved in the testing.

Surface Hardness Testing

Surface hardness methods are generally used to indicate the strength level or quality of a material rather than to detect flaws. Hardness in these tests refers to the resistance a material offers to indentation by a object. Indentation is produced under static or impact loading conditions. The most common applications are in testing metals and concrete.

Static Indentation Tests

Static indentation tests are primarily used in testing metals. They usually involve indenting the surface with an indenter of fixed geometry under specified loads.[42] The indenter has a small point and thus at the point of contact produces stresses high enough to cause the metal to yield. A permanent indentation results. The magnitude of the indentation will depend on the strength of the metal, the applied load, and the geometry of the indenter. Therefore, by measuring the size of the indentation under a given set of conditions, one can get an approximate measure of the strength. Portable hardness testers are available for in-place testing of metal structures.

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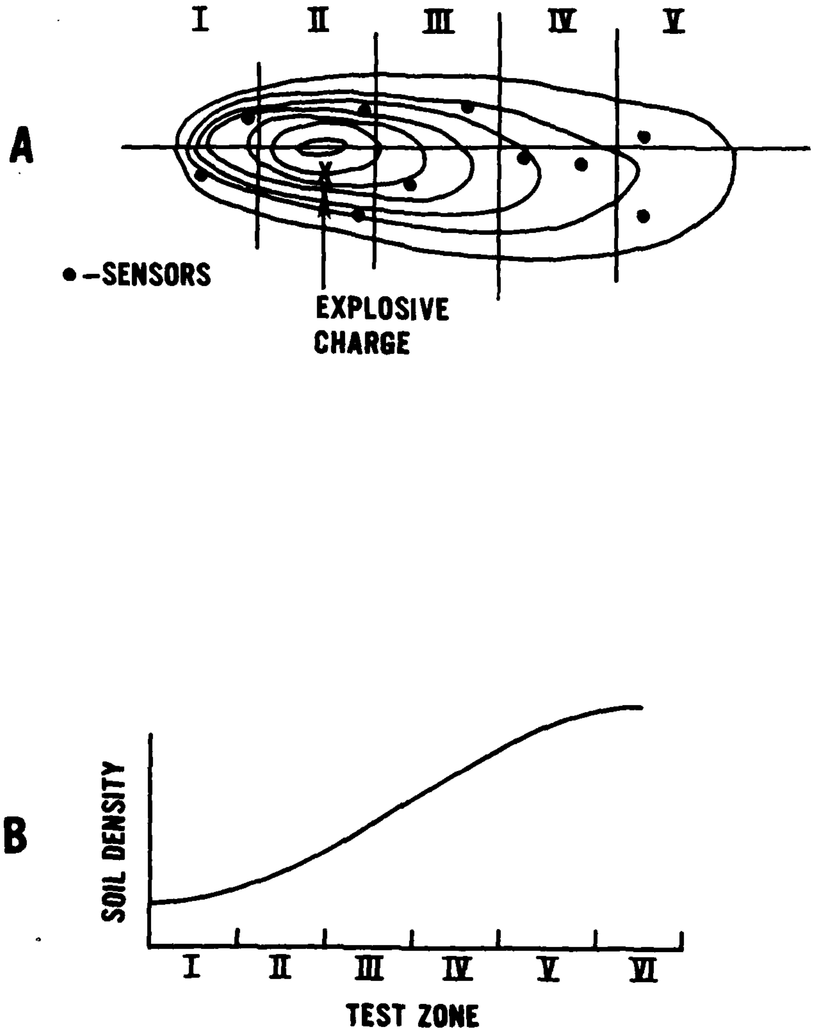
[41] G. W. Sevall, Nondestructive Testing of Construction Materials and Operations, Technical Report M-67/AD774847 (CERL, 1973).

[42] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).



A = shock wave pattern.
B = seismic test data plot.

Figure 14. Schematic of seismic testing. (From G. W. Sevall, Nondestructive Testing of Construction Materials and Operations, Technical Report M-67/ADA774847 [CERL, 1973].)

Standard Methods. There are three widely used methods for hardness testing metals. The Brinell method involves applying a constant load (500, 1500, or 3000 kg) on a 0.4-in. (10-mm)-diameter hardened steel ball-type indenter, and measuring the diameter of the indentation with a microscope. A hardness number is determined by substituting the values of the applied load, ball diameter, and indentation diameter into a standard formula. An example of a Brinell test result would be 400 HB; 400 is the number calculated from the standard formula, "H" stands for hardness, and "B" for Brinell. For weaker metals, one would use a smaller load to cause the indentation.

The Vickers method is similar to the Brinell method, except that a square-based, pyramidal diamond indenter is used, and the applied loads are much smaller. The diagonal of the square indentation is measured, and its value and the applied load are substituted into a standard equation to calculate the Vickers hardness number (HV).

The most common method is the Rockwell hardness test, which measures the depth of additional permanent indentation that occurs as the load is increased from a small load to the test load. The test instrument measures the depth automatically, and the hardness number is read directly from a scale on the instrument. The Rockwell test can be performed much faster than the previously described methods. There are 15 Rockwell hardness scales -- five different indenters and three different loads. A hardness number of 60 on the Rockwell C scale would be designated 60 MRC. The variety of scales permits testing a wide range of metals from very soft (weak) to very hard (strong).

Usefulness of the Hardness Number. Tables are available that permit conversion of the hardness number from one test method to the equivalent number of another test method (for example, ASTM E 140).[43] There are also tables which give the approximate tensile strengths of metals corresponding to the different hardness numbers. Care must be taken in using the strength tables because each applies to only certain types of metals.

Rebound Hammer Method

The rebound method is based on the rebound theories of Shore.[44] He developed the Shore Scleroscope method in which the height of rebound of a steel hammer dropped on a metal test specimen is measured. The only commercially available instrument based on the rebound principle for testing concrete is the Schmidt Rebound Hammer.[45]

This technique has gained wide acceptance by researchers and concrete inspectors. It is one of the most universally used nondestructive test methods for determining the in-place quality of concrete, and for deciding when forms may be removed. According to J. R. Clifton, standards have been drafted in Poland and Romania for the rebound hammer. The British Standards Institution has issued Building Standard 4408 which covers nondestructive test methods for concrete, and includes the rebound hammer method in part 4 of the Standard.[46] Recently, ASTM issued Standard C 805, which gives procedures for the use of the rebound hammer.[47]

Description of Method. The Schmidt Rebound Hammer consists of a steel weight and a tension spring in a tubular frame (Figure 15). When the plunger of the hammer is pushed against the surface of the concrete, the steel weight is retracted against the force of the spring. When the weight is completely

[43] Standard Hardness Conversion Tables for Metals, ASTM 140.
[44] A. T. Shore, "Properties of Hardness in Metals and Materials," Proceedings of the ASTM, Vol 9 (1911), p 733.
[45] E. Schmidt, "A Nondestructive Concrete Test, Concrete," Proceedings of the ASTM Vol 59, No. 8 (1951), p 34.
[46] J. R. Clifton, Nondestructive Test to Determine Concrete Strength -- A Status Report, NBSIR 75-729 (National Bureau of Standards, 1975).
[47] Test for Rebound Number of Hardened Concrete, ASTM C 805 (1979).

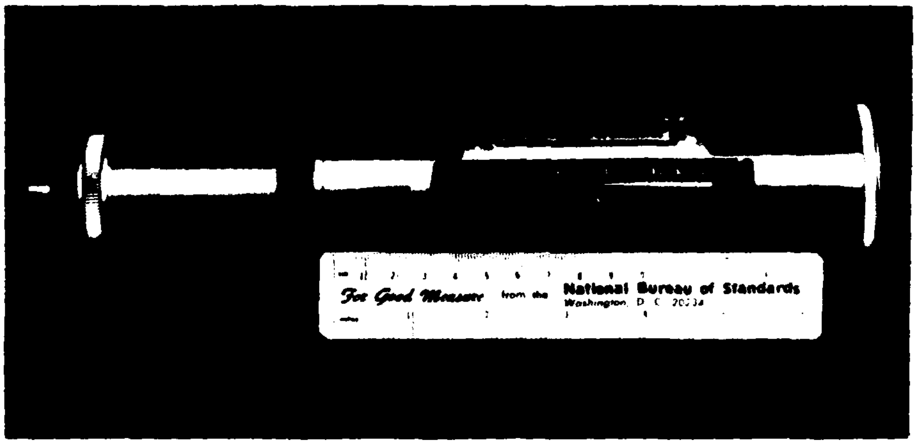


Figure 15. Schmidt Rebound Hammer.

retracted, the spring is automatically released, the weight is driven against the plunger, and it rebounds. The rebound distance is indicated by a pointer on scale that is usually graduated from zero to 100; the rebound readings are termed R-values. The determination of the R-values is outlined in the manual supplied by the manufacturer. R-values indicate the hardness of the concrete; the values increase with the hardness of the concrete.

Each hammer has a calibration chart, showing the relationship between compressive strength of concrete and rebound readings. However, rather than placing too much confidence in the calibration chart, users should develop their own for each concrete mix and each rebound hammer.

Applications. Numerous investigators have shown that there is some correlation between the compressive strength of concrete and the hammer rebound number.[48] There is, however, extensive disagreement about the accuracy of the strength estimates from rebound measurements.[49] Mitchel and Hoagland found that the coefficient of variation for estimated compressive strength, for a wide variety of specimens from the same concrete, averaged

[48] P. H. Peterson and V. W. Stoll, "Relation of Rebound Hammer Test Results to Sonic Modulus and Compressive-Strength Data," Proceedings of the Highway Research Board, Vol 34 (1955), p 387; C. Boundy and G. Hondrus, "Rapid Field Assessment of Strength of Concrete by Accelerated Curing and Schmidt Rebound Hammer," Journal of the American Concrete Institute, Vol 61, No. 1 (1964), p 1; D. J. Victor, "Evaluation of Hardened Field Concrete with Rebound Hammer," Indian Concrete Journal, Vol 37, No. 11 (1963), p 407.

[49] G. W. Greene, "Test Hammer Provides New Method of Evaluating Hardened Concrete," Journal of the American Concrete Institute, Vol 26, No. 3 (1954), p 249; "Discussion of G. W. Greene, 'Test Hammer Provides New Method of Evaluating Hardened Concrete,'" Journal of the American Concrete Institute, Vol 27, No. 4 (1955), p 256.

18.8 percent.[50] Arni found that the rebound hammer gave a less reliable estimate of compressive strength than the Windsor Probe.[51] Some investigators have attempted to establish correlations between the flexural strength of concrete and the hammer rebound number. Relationships similar to those for compressive strengths were obtained, except that the statistical variations were even greater.[52]

Mitchel and Hoagland attempted to correlate rebound numbers with the modulus of specimens.[53] They concluded that no valid correlations could be made. Peterson and Stoll, and Klieger have developed some empirical relations between the dynamic modulus of elasticity and hammer rebound.[54]

Advantages. The Schmidt Rebound Hammer is a simple and quick method for the nondestructive testing of concrete in place. The equipment is inexpensive, costing less than $1000, and can be operated by field personnel with a limited amount of instruction.

The rebound hammer, like the Windsor Probe, is very useful in assessing the general quality of concrete and for locating areas of poor quality concrete. A large number of measurements can be rapidly taken so that large exposed areas of concrete can be mapped within a few hours.

Limitations. The Schmidt Rebound Hammer, however, has recognized limitations. The rebound measurements on in situ concrete are affected by:

1. Smoothness of the concrete surface
2. Moisture content of concrete
3. Type of coarse aggregate

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[50] L. J. Mitchel and G. G. Hoagland, Investigation of the Impact-Type Concrete Test Hammer, Highway Research Board Bulletin 305 (1961), p 14.

[51] H. T. Arni, Impact and Penetration Resistance Tests of Portland Cement Concrete, Federal Highway Administration Report No. FHWA-RD-73-5 (1972).

[52] "Discussion of G. W. Greene, 'Test Hammer Provides New Methods of Evaluating Hardened Concrete,'" Journal of the American Concrete Institute, Vol 27, No. 4 (1955), p 256; C. H. Williams, Investigation of the Schmidt Concrete Test Hammer, Miscellaneous Report No.6-267 (U.S. Army Engineer Waterways Experiment Station, 1958).

[53] L. J. Mitchel and G. G. Hoagland, Investigation of the Impact-Type Concrete Test Hammer, Highway Research Board Bulletin 305 (1961), p 14.

[54] P. H. Peterson and V. W. Stoll, "Relation of Rebound Hammer Test Results to Sonic Modulus and Compressive-Strength Data," Proceedings of the Highway Research Board, Vol 34 (1955) p 387; P. Klieger, Discussion of P. H. Peterson and V. W. Stoll, "Relation of Rebound Hammer Test Results to Sonic Modulus and Compressive-Strength Data," Proceedings of Highway Research Board, Vol 34 (1955), p 392.

4. Size, shape, and rigidity of specimen, e.g., a thick wall or beam
5. Carbonation of the concrete surface.[55]

The rebound method is a rather imprecise test and does not provide a reliable prediction of the strength of concrete.

Thermal Inspection Methods

The presence of discontinuities in an object, such as cracks, voids, or inclusions, will change the heat transfer characteristics of the object. Thus, if there is a transient heat flow condition, there will be nonuniform surface temperatures. The pattern of the surface temperatures can be used as an indirect indicator of subsurface anomalies.[56] Thermal inspection can also detect anomalous operating characteristics of a system, such as overloaded electrical wiring or heat loss through walls and roofs of buildings. The following discussion addresses primarily the application of thermal inspection to detect anomalies in the internal structure of test objects such as structural metallic components and roofing systems.

Principles of Thermal Inspection

To establish the condition for thermal inspections, a transient heat flow situation must exist or be created. If necessary, this can be done by applying a temporary heat source to the front or back surface of the test object. The flow of heat from the warm to the cold surface will be affected by the material's thermal diffusivity, which is itself a function of the material's thermal conductivity, density, and specific heat. If there are discontinuities which have thermal diffusivities different from that of the bulk material, local "hot" or "cold" spots will exist on the surfaces directly over the location of the voids. Therefore, by measuring the pattern of surface temperatures under heat flow conditions, subsurface flaws can be detected.

Surface temperatures can be determined by contact, and noncontact inspection methods. With contact methods, the surface is covered with a temperature-sensitive material, and differences in surface temperature are recorded as a pattern on the coating material. Examples of coatings developed for this application are: heat sensitive paints and papers; phosphor coatings the fluorescence of which, under ultraviolet light, is affected by temperature; melting point coatings which melt when a specific temperature is reached; and liquid crystals which change color as their temperatures vary.

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[55] V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, American Concrete Institute (ACI) Monograph No. 9 (1976); "Discussion of G. W. Greene, 'Test Hammer Provides New Method of Evaluating Hardened Concrete,'" Journal of the American Concrete Institute, Vol 27, No. 4 (1955), p 256; G. A. Erickson, Investigation of the Impact-Type Concrete Test Hammer, Model II, Concrete Laboratory Report C-928 (Division of Engineering Laboratories, Dept. of the Interior, 1959).

[56] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

Contact methods are generally not very sensitive, have relatively long response times, and require an application procedure before thermal inspection. Noncontact methods permit remote sensing of the thermal patterns, and are the most popular thermal inspection methods.

Infrared Thermography

Principle of Method. An object having a temperature above absolute zero will radiate electromagnetic waves. The wavelengths of the radiation fall within certain bands, depending on the temperature. For example, at room temperature, the wavelengths are typically from 4 to 40 micrometers, with a peak wavelength of about 10 micrometers.[57] At very high temperatures, the wavelengths of the emitted radiation are reduced to less than 1 micrometer and fall within the visible spectrum, which explains why some metals give off a red color when heated to high temperatures. The longer wavelength radiation associated with room temperature is not visible to the eye. This is infrared radiation. By using instruments that can detect infrared radiation, differences in surface temperatures can be "seen." This is the basis of the thermal inspection method; known as infrared thermography.

The rate of radiant energy emission per unit area of surface (W) is given by the Stefan Boltzmann Law:

$$W = e\sigma T^4 \quad \text{[Eq 3]}$$

where: T = the absolute temperature

e = the emissivity

σ = the Stefan-Boltzmann constant (5.67×10^{-12} watt/cm^2/$^oK^4$).

Thus, changes in the temperature of a surface produce more than proportional changes in emitted energy, and this allows the testing equipment to detect temperature differences as low as 0.2°C. Emissivity refers to the efficiency of energy radiation by the surface. The maximum radiation efficiency occurs in a "black body," and this is given an emissivity value of 1. All real surfaces have an emissivity less than 1; polished metallic surfaces have low emissivity, while roughly textured nonmetals have high emissivity. Since detection methods are based on the intensity of emitted radiation, a change in emissivity at various points on the surface may be incorrectly interpreted as a change in temperature. Surfaces with nonuniform or low emissivity can be painted with high emissivity coatings.

Remote Inspection. Infrared thermography permits remote inspection of the test object. This is possible because air is practically transparent to the infrared wavelengths associated with conditions near room temperature.[58] However, high water content will reduce the transmission of infrared radiation

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[57] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Conmtrol, 8th Edition (American Society of Metals, 1976).

[58] D. R. Jenkins, L. J. Knab, and R. G. Mathey, Moisture Detection in Roofing by Nondestructive Means, A State-of-the-Art Survey, National Bureau of Standards Technical Note (In Press).

through air, so problems may arise when the weather is humid. Semiconductor crystals are most often used to detect infrared radiation. Their electrical properties are altered by incident infrared radiation. For best sensitivity, the crystals should be kept cold with liquid nitrogen. This places some limitations on the portability of the detection systems. Dewar flasks are needed to hold the liquid nitrogen, and the nitrogen needs to be replaced as it evaporates.

Infrared Scanners and Display. Operating on a scanning principle similar to television, infrared scanners allow the user to view a picture of the test object's surface (Figure 16). Through a system of special mirrors, the surface is scanned, a small spot at a time; the intensity of radiation is measured by the detector and is displayed on a cathode ray tube. The horizontal and vertical scans occur so quickly that a picture (thermogram) of the surface is reconstructed on the cathode ray tube. The picture is presented as shades of gray corresponding to variations in surface temperatures of the viewed object. A calibration strip is also shown so that the shades can be converted to absolute temperatures if desired. It is also possible to have a color display showing different temperatures in different colors.

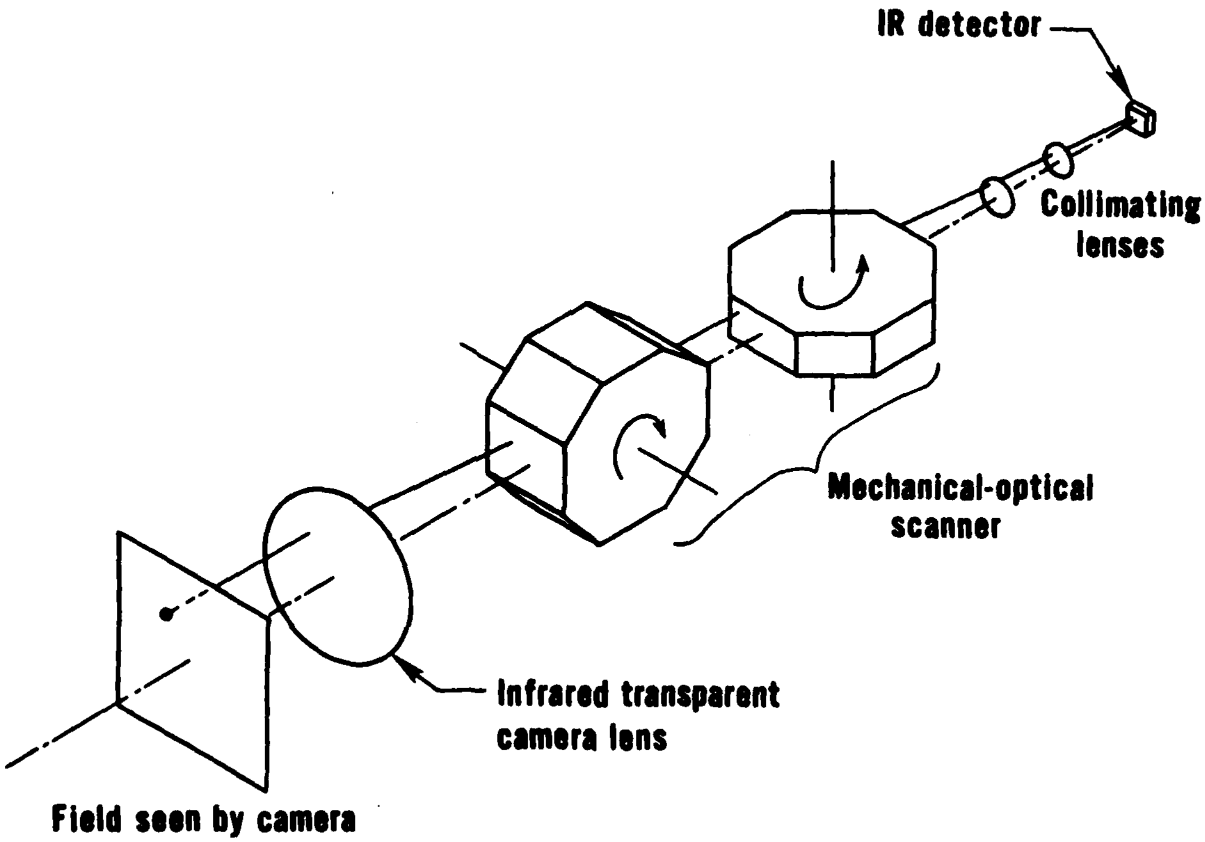

Figure 16. Schematic of infrared camera.

Applications

Thermal inspection methods have been applied for detecting disbonds in laminated materials, entrapped moisture, material density gradients, and anomalies in casting.[59] In the construction area, infrared thermography has been applied to compare thermal resistances of roofs, to detect water penetration into built-up roofs, to detect heat loss through walls and roofs of buildings, and to detect overloaded electrical circuits.[60] Recently, infrared thermography has been used to detect deteriorated regions in bridge decks.[61]

Advantages

Thermal inspection equipment is generally portable, and a permanent record (photograph) can be made of the inspection results. By using infrared thermography, inspections can be performed without direct access to the surface, and large areas can be rapidly inspected.

Limitations

In determining the size and location of detectable flaws, it should be recognized that under heat flow conditions the surface temperature patterns will be a function of the type and size of the discontinuity, the heat intensity applied or flowing to the surface of the object, and the observation time.[62] The sensitivity of infrared thermography in detecting internal flaws is a complex function of these variables. Therefore, the results of such inspections should be carefully interpreted.

Ultrasonic Pulse Methods

In the ultrasonic pulse methods, sound waves which are beyond the audible range are induced in a test object by a piezoelectric transducer, and either reflected waves or those passing through the object are detected by a similar type of transducer.[63] When reflected waves are detected, the technique is called "pulse-echo," and the transmitting transducer may also act as the

[59] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

[60] D. R. Jenkins, L. J. Knab, and R. G. Mathey, Moisture Detection in Roofing by Nondestructive Means, A State-of-the-Art Survey, National Bureau of Standards Technical Note (In Press).

[61] D. G. Manning and F. B. Holt, "Detecting Delamination in Concrete Bridge Decks," Concrete International, Vol 2, No. 11 (1980), pp 34-41.

[62] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976).

[63] Metals Handbook, Vol 11; V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, ACI Monograph No. 9 (1976); A. L. Smith, "Ultrasonic Testing Fundamentals," Lesson 5, Fundamentals of Nondestructive Testing, (Metals Engineering Institute, 1977); J. F. Lovelace, "Ultrasonic Testing Equipment," Lesson 6, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); A. J. Moberg, "Ultrasonic Testing Applications," Lesson 7, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); E. A. Whitehurst, Evaluation of Concrete Properties From Sonic Tests, ACI Monograph No. 2 (1966).

receiver. Waves passing through the object (velocity method) are detected with a second transducer, i.e., a receiving transducer.

Ultrasonic inspection is based on two principles: (1) the velocity of the acoustic waves in a material is a function of that material's elastic constants and density; and (2) when an acoustic wave encounters an interface between dissimilar materials, a portion of the wave is reflected. The amount of reflection depends on the mismatch in acoustic impedance (product of wave velocity and density) of the materials, with the amount of reflection increasing with the mismatch.

Ultrasonic Pulse Velocity Method

The ultrasonic pulse velocity is one of the most universally used NDE methods for assessing the quality of concrete.

Principle of Method. The ultrasonic pulse velocity method measures the travel time of an ultrasonic pulse passing through a material. The pulse generated by an electroacoustic transducer is picked up by a receiver transducer and amplified. The time of travel of the pulse is measured electronically.[64] A commercial instrument for measuring the ultrasonic pulse velocity of concrete is shown in Figure 17.

Figure 17. Ultrasonic pulse velocity equipment.

[64] E. A. Whitehurst, Evaluation of Concrete Properties From Sonic Tests, ACI Monograph No. 2 (1966).

When a mechanical pulse is applied to a material by an electroacoustic transducer, waves are induced in the material. Longitudinal waves are used most often in testing concrete. These waves are transmitted by particles vibrating parallel to the direction of propogation. The waves' velocity, controlled by the elastic properties and the density of the material, is virtually independent of the geometry of the object being tested.

If a longitudinal wave encounters a discontinuity such as a crack or void, it may "bend," i.e., be diffracted around the discontinuity. This increases the internal distance the wave must pass between the transmitting and pickup transducers, and consequently its travel time increases. Therefore, for a given separation of the transducers, and for a given concrete, the travel time of a longitudinal wave will be affected by changes in density and elastic properties along the travel path.

Several ultrasonic pulse velocity units are commercially available for testing concrete; these cost about $4000. Some models can be used to test concrete as thick as 75 ft (30 m).

Application for Assessment of Condition of Concrete. The ultrasonic pulse velocity method is best for nondestructive evaluation of the uniformity of in-place concrete. (ASTM C 597 gives the standard test procedure.)[65] For example, velocity measurements have been successfully used to detect deteriorated regions in concrete bridges and to check the uniformity of concrete in walls. In general, if substantial variations in pulse velocities are found in a structure, without any apparent reason (such as intentional changes in materials, concrete mix, or construction procedures), this indicates that the concrete is unsound.

A general rating which has been proposed to assess the relative quality of concrete is presented in Table 15.[66] These criteria should be used with caution because differences in the qualities of concrete cannot be as sharply delineated as indicated in Table 15. In addition, velocity is affected by the density and amount of aggregate in the concrete. A crude assessment of the quality of similar types of concrete can be made, however, using these criteria. For example, if one concrete has a pulse velocity of 15,000 ft/sec (4570 m/sec), while another concrete with a similar composition has a velocity below 10,000 ft/sec (3050 m/sec), then there is clearly a significant difference in their qualities.

Estimation of Strength Properties of Concrete. Many investigations have attempted to correlate compressive and flexural strengths of concrete with pulse velocity.[67] Some correlations have been obtained in laboratory studies, provided that mix proportions, the cement, types of aggregate, and curing conditions were not varied. If these factors were altered, however, no usable correlations were obtained. For example, Parker compared pulse velocities and compressive strengths for concretes made from only one type of aggregate, but

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[65] Test for Pulse Velocity Through Concrete, ASTM C 597 (1971).

[66] J. R. Leslie and W. J. Cheesman, "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures," Journal of the American Concrete Institute, Vol 21, No. 1 (1949), Proceedings, Vol 46, pp 17-36.

[67] E. A. Whitehurst, Evaluation of Concrete Properties From Sonic Tests, ACI Monograph No. 2 (1966).

Table 15

Pulse Velocities in Concrete
(Adapted from J. R. Leslie and W. J. Cheesman, "An Ultrasonic Method of Studying Deterioration and Cracking in Concrete Structures," Journal of the American Concrete Institute, Vol 21, No. 1 [1949], Proceedings, Vol 46, pp 17-36.)

Feet per Second	(Meters per Second)	General Condition
Above 15,000	(4570)	Excellent
12,000-15,000	(3660-4570)	Good
10,000-12,000	(3050-4570)	Questionable
7,000-10,000	(2130-3050)	Poor
Below 7000	(2130)	Very Poor

containing different cements from different sources and a variety of admixtures. His analysis of the total data indicates that at the 95 percent confidence level the estimated strength of 4440 psi (30.7 MN/m^2) concrete ranged from about 2100 to 6000 psi (14.5 to 41.8 MN/m^2).[68] Obviously, the ultrasonic pulse method cannot be used to obtain reliable estimates of compressive strength when the composition of concrete in a structure is unknown.

Jones probably offers the best concluding remarks regarding strength prediction from wave propagation methods: "In spite of some of the promising results of the early investigations, it must be concluded that no general relation has been found between the dynamic modulus of elasticity and its flexural or compressive strength."[69] This statement still holds if one substitutes "pulse velocity" for "dynamic modulus of elasticity."

Extraneous Effects on Velocity Measurements. The measurement of the pulse velocity of concrete is affected by several factors which are not intrinsic properties of concrete, and, therefore, are not a function of the quality or strength of concrete:[70]

1. Smoothness of concrete at transducer contact area. Good acoustical contact between the transducers and concrete is required. In addition, a coupling agent such as an oil or a jelly must be used.

2. Concrete temperatures outside the range between 41^o and 86^{o}F (5^o and 30^{o}C) affect the measured pulse velocity. Below this temperature range, the velocity is increased, and above, the velocity is decreased.

[68] W. E. Parker, "Pulse Velocity Testing of Concrete," Proceedings of the ASTM, Vol 53 (1953), p 1033.
[69] R. Jones, Nondestructive Testing of Concrete (Cambridge University Press, 1962).
[70] V. M. Malhotra, Testing Hardened Concrete: Nondestructive Methods, ACI Monograph No. 9 (1976).

3. Moisture condition of concrete. Pulse velocity generally increases as the moisture content of concrete increases, while compressive strength decreases as moisture content increases.

4. Presence of reinforcing steel. The pulse velocity in steel is 1.2 to 1.9 times the velocity in concrete. Measurements made near steel reinforcing bars, therefore, may not be representative of the concrete. If possible, measurements should be made perpendicular to the longitudinal axis of the bars. If measurements must be made parallel to the longitudinal axis of the steel bars, crude correction factors are available.

Ultrasonic Pulse Echo Method

Principle of Method. In the ultrasonic pulse echo method, waves which are reflected off discontinuities (e.g., cracks and voids) and from interfaces (e.g., those between concrete and steel or between concrete and air) are recorded. Both the transmitting and receiving transducers are contained in the same probe; thus, only waves which are reflected back at nearly 180 degrees out of phase with the incident waves are detected. The penetrating ability of the ultrasonic pulse and the minimum size of detectable flaws are influenced by the frequency of the generated waves. High frequency results in less penetration but better sensitivity than low frequency.

Applications. Echo techniques have been extensively used to identify and locate discontinuities and defects in metals and welds.[71] The echo technique is one of the most versatile and accepted NDE methods for metals. However, it has not been used often with concrete -- largely because the extensive pore system, the presence of cracking, and the heterogeneous nature of concrete cause multiple reflections when very high frequency pulses are used. Therefore, the reflected waves are significantly attenuated and the interpretation of the observations complicated. It may be possible, however, to combine the echo method with acoustic impact (see Acoustic Impact Method, p 27) so that low frequency waves are generated. These would be insensitive to microscopic flaws but could be used to detect large discontinuities. Commercial equipment is not yet available for such testing.

Advantages. Ultrasonic pulse-echo inspection offers several advantages over other NDE methods -- such as gamma radiography -- capable of detecting internal flaws in a test object.[72] For example, acoustic waves have excellent penetrating ability, and with proper instrument selection, thick sections of 32.8 ft (10 m) or more can be inspected. Very small flaws may be detected, and their location and geometry estimated with reasonable accuracy. In addition, test results are immediately available, the equipment is lightweight and portable, and acoustic waves pose no health hazard.

[71] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976); A. L. Smith, "Ultrasonic Testing Fundamentals," Lesson 5, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); J. F. Lovelace, "Ultrasonic Testing Equipment," Lesson 6, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977); A. J. Moberg, "Ultrasonic Testing Applications," Lesson 7, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977).

[72] Metals Handbook, Vol 11.

Limitations. Because of the indirect nature of flaw detection by ultrasonic pulse-echo inspection, personnel with a high level of expertise are needed to plan an inspection program. A thorough understanding of the nature of the interactions between the acoustic waves and different discontinuities is required in order to interpret test results properly. The physical testing, on the other hand, may be performed by technicians after proper training. Before ultrasonic inspection equipment can be used, calibration and referencing with standards must be performed; otherwise, test results have no meaning. The nature of the calibrations will depend on the particular inspection program.

Visual Inspection

Surface defects often can be detected visually using methods to improve ordinary observation. Optical magnification or other techniques which can be used to increase the apparent size of surface cracks are covered in this section.

Optical Magnification

Available magnifying instruments range from simple, inexpensive glasses to expensive microscopes. Some fundamental principles about the operating characteristics of magnification instruments should be understood before a system is chosen for a particular application. For example, the focal length decreases as the magnification power increases. This means that when high magnification is desired, the primary lens must be placed close to the test object. The field view (the portion of the object that can be seen at any instant) also decreases as magnification power increases. A small field of view means that it will be tedious to examine a large surface area. Another important characteristic is the depth of field -- the elevation difference of rough textured surfaces that can be viewed in focus simultaneously; the depth of field decreases as the magnification power of the instrument increases. Therefore, to inspect a rough-textured surface, a magnification power should be selected that gives a large enough depth of field so that the "hills" and "valleys" are simultaneously in focus. Finally, the illumination intensity required to clearly see surface flaws will increase as the magification power increases. High magnification may require using a light source to supplement the available lighting.

A useful tool for field inspection is a pocket magnifier with a built-in viewing scale, which allows measurement of flaw dimensions. A stereomicroscope is very useful when a three-dimensional view of the surface is required. With this instrument, one can determine whether a wide crack is shallow or extends deep into the object. If calibrated, a stereomicroscope can also be used as a depth gage to measure the approximate height of surface irregularities.

Fiberscope

Another useful instrument is the fiberscope, which is composed of a bundle of flexible optical fibers and lens systems. The fiberscope can be inserted through a small access hole so that the inside of a cavity can be seen. Some of the fibers in the bundle carry light into the cavity and

illuminate the field of view. The viewing head can be rotated so that a wide viewing angle is possible from a single access hole. A fiberscope, because of the discrete nature of light transmission of the fibers, may not have as good a resolution ability as a boroscope, which is a straight, rigid tube using a lens system for viewing. The best resolution is obtained with an instrument having small-diameter fibers in which the fiber density per unit area is high. To use a fiberscope, one must drill access holes if natural channels are not present, and the holes must intercept cavities. The acoustic impact technique (p 27) can be used to locate hollow spots for subsequent fiberscope inspection.

Liquid Penetrant Inspection

In this method a highly visible dye is used to coat the surface to be inspected.[73] Any cracks open to the surface will soak up the dye because of surface tension and capillary effects. After application of the dye, the surface is cleaned. However, the dye which penetrated into cracks remains and reveals the presence of cracks. The method is one of the most inexpensive inspection tools, but it only permits detection of open flaws on the surface of the test object.

Description of Method. Dye penetration inspection involves the following steps: (1) cleaning the surface, (2) applying the dye, (3) removing excess dye from the surface, (4) applying a developer, and (5) interpreting the results.

The objective of the cleaning is to remove foreign matter from cracks so that the dye can penetrate. The specific procedures depend on the condition of the surface. Care must be taken to ensure that the cleaning process does not smear the cracks or fill them with residues. For example, sandblasting a soft metal may "hammer" the surface so much that cracks become closed and undetectable.

The dye may be applied to the surface by spraying, painting, or dipping. Two types of dye are available: one is for viewing under ordinary light and is usually a brilliant red color, the other is fluorescent and viewed under ultraviolet light. Fluorescent dyes offer the best sensitivity for detecting small cracks. The dye is allowed to remain on the surface from 10 to 30 minutes (dwell time) before the surface is cleaned.

Cleaning can be done by flushing the surface with water or by wiping with a rag dampened with solvent. For water cleaning, an emulsifying agent is needed so that the dye can be completely removed with water. The agent is either already included in the dye, or it is added to the coated surface before washing. This phase is very important; all excess dye must be removed, otherwise some indications of cracks will be false. If the surface is very porous, inspection by this method may be difficult; if dye is not removed from

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[73] Metals Handbook, Vol 11, Nondestructive Inspection and Quality Control, 8th Edition (American Society of Metals, 1976); E. O. Lomerson, "Liquid Penetrants," Lesson 2, Fundamentals of Nondestructive Testing (Metals Engineering Institute, 1977).

the pores, there will be a loss of contrast because the surface will take on a color that is a light shade of the dye. If the dye is removed from all pores, it probably will be removed from some of the cracks as well.

After cleaning, the surface is allowed to dry, and a developer is added. Developer is a fine powder which: (1) provides a uniform, colored background to increase contrast, and (2) has a blotting effect, thereby drawing up the dye from the cracks. The blotting action increases the apparent width of the cracks so that they are clearly visible. Developer can be applied as a dry powder or as a paint. The thickness of the developer layer is important; if it is too thin, there will not be good contrast, and if it is too thick, it may mask the cracks.

Finally, the prepared surface is inspected. If the application was done correctly, the cracks will be clearly shown.

However, the inspector needs to be familiar with the patterns associated with "irrelevant indications," i.e., patterns not from cracks but from other sources, such as improper cleaning.

Applications and Limitations. Although dye penetrant inspection relies on simple principles, a certain amount of skill is necessary to do the process correctly. The operator needs to recognize what materials to use for a particular application, and to understand how the materials respond to different temperature conditions. Portable kits are available with the various chemicals in aerosol cans, thus making field inspection possible. The technology is now geared primarily toward inspection of metals; the applicability of the procedures to masonry or concrete structures having surfaces of high porosity has not been demonstrated.

Combinations of Nondestructive Evaluation Methods

While no single NDE method may be entirely satisfactory for predicting the strength or quality of a material, combinations of methods which respond to different factors may give more definite information. The combined NDE approach has been developed mainly for evaluating concrete; therefore, only applications to concrete will be described.

The results of two methods can be combined in a linear equation of the form:

$$f_c' = A(NDE_1) + B(NDE_2) + C \qquad [Eq\ 1]$$

where f_c' is the estimated compressive strength from the combined method, NDE_1 and NDE_2 are the results of the individual methods, and A, B, and C are empirically determined constants.

Two combinations often used are the ultrasonic pulse velocity method and the measurement of the damping constant of concrete,[74] and the ultrasonic pulse velocity and pulse attenuation methods.[75] These combinations are essentially laboratory research techniques and therefore will not be discussed further.

The most popular combination has been the ultrasonic pulse velocity method and the rebound hammer.[76] This combination has been used primarily in Europe, with the most exhaustive studies being carried out by Facaoaru.[77] In this combined approach, measurements of ultrasonic pulse velocity and rebound number are made on in situ concrete. The pulse velocity and rebound number are substituted into a previously derived regression equation to predict compressive strength. It is generally believed that the multiple regression equation should give a more accurate estimate of compressive strength than either of the individual measurements alone.

For standard concrete mixes, Facaoaru has developed calibration charts from which the compressive strengths can be estimated when the pulse velocities and rebound numbers are known.[78] Correction factors have also been developed to be used in the case of nonstandard concrete mixes. This combined method has been used often in Romania to estimate the compressive strength of in situ concrete.[79] Based on his experiences, Facaoaru contends that the

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[74] J. G. Wiebenga, A Comparison Between Various Combined Nondestructive Testing Methods to Derive the Compressive Strength of Concrete, Report No. B1-68-61/IHI.8 (Insitut TNO Voor Bouwmaterialen en Bouwconstructies, Delft, Netherlands, 1968).

[75] A. Galan, "Estimate of Concrete Strength by Ultrasonic Pulse Velocity and Damping Constant," Journal of American Concrete Institute, Vol 64, No. 10 (1967), p 678.

[76] R. Jones and I. Facaoaru, "Analysis of Answers to a Questionnaire on the Ultrasonic Pulse Technique," Materiaux et Constructions/ Materials and Structures, Vol 1, No. 5 (1968), p 457.

[77] I. Facaoaru, "Nondestructive Testing of Concrete in Romania, "Paper 4C, Symposium on Nondestructive Testing of Concrete and Timber (London: Institution of Civil Engineers, 1969); I. Facaoaru, I. Dumitrescu, and L. Constaninescu, Concrete Strength Determination by Nondestructive Combined Methods, RILEM Report, Aachen, 41 (1966); I. Facaoaru, I. Dumitrescu, and Gh. Stamate, New Developments and Experience in Applying Combined Nondestructive Methods for Testing Concrete, RILEM Report, Varna, 26 (1968); I. Facaoaru, "Chairman's Report of the RILEM Committee on Nondestructive Testing of Concrete," Materiaux et Constructions/Materials and Structures, Vol 2, No. 10, (1969), p 253.

[78] I. Facaoaru, "Nondestructive Testing of Concrete in Romania," Paper 4C, Symposium on Nondestructive Testing of Concrete and Timber (London: Institution of Civil Engineers, 1969).

[79] Facauoaru, "Nondestructie Testing"; I. Facaoaru, I. Dumitrescu, and Gh. Stamate, New Developments and Experience in Applying Combined Nondestructive Methods for Testing Concrete, RILEM Report, Varna, 26 (1968).

combined method offers the following accuracy in predictions of compressive strengths:

1. When composition is known and test specimens or cores are available for calibration purposes, accuracy is within 10 to 15 percent.

2. When only the composition of the concrete is known, accuracy is within 15 to 20 percent.

3. When neither the composition is known nor test specimens or cores are available, accuracy is within 20 to 30 percent.[80]

This suggests that for case 3, the combined method gives no better prediction of the compressive strength than can be obtained by measuring only the ultrasonic pulse velocity or only the rebound number; in case 2, the improvement is marginal. Therefore, only when the concrete is well characterized is this combined method better than the individual nondestructive methods.

[80] I. Facaoaru, I. Dumitresch, and G. L. Stamate, New Developments and Experience in Applying Combined Nondestructive Methods for Testing Concrete, RILEM Report, Varna, 26 (1968).

4 CONCLUSION

This report has identified NDE methods for building materials and systems. The report is intended to help inspectors choose appropriate NDE methods for specific building materials, systems, and components. Important properties of building materials and important performance requirements of systems and components have been explained, and appropriate NDE methods recommended.

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APPENDIX:
ASTM STANDARDS FOR NDE METHODS

ASTM has recognized the need for standards covering nondestructive evaluation methods for a variety of materials and applications. ASTM standards for NDE methods for concrete are listed in Table A1. Some standards for other common NDE methods are listed in Table A2. New ASTM standards for NDE are periodically being prepared; they can be located by reviewing the index to ASTM standards which is published annually.

Table A1

ASTM Standards for NDE Methods for Concrete

NDE Method	ASTM Standards and Designation
Rebound Hammer	Test for rebound number of hardened concrete: C 805
Penetration Probe	Test for penetration resistance of hardened concrete: C 803
Ultrasonic Pulse Velocity	Test for pulse velocity through concrete: C 597
Nuclear Moisture Meter	Standard test method for moisture content of soil and soil-aggregate in place by nuclear methods (shallow depth): D 8017
Cast-in-Place Pullout	Standard test method for pullout strength of hardened concrete: C 900
Visual	Standard recommended practice for examination of hardened concrete in construction: C 823

Table A2

ASTM Standards for Some NDE Methods

NDE Method	ASTM Standard and Designation
Eddy Current Method	Method of Test for Electrical Conductivity by Use of Eddy Current: B 342
Hardness Testing	Conversion Tables for Metals (Relationship Between Brinell Hardness, Diamond Pyramid Hardness, Rockwell Hardness and Rockwell Superficial Hardness): 140
	Brinell, Metallic Materials: E 10
	Diamond Pyramid of Metallic Materials: E 92
	Indentation Hardness of Plastics by Means of a Durometer: D 1706
	Portable Hardness Testers: E 110
	Rapid Indentation Hardness Testing of Metallic Materials: E 103
	Rockwell, and Rockwell Superficial, Metallic Materials: E 18
Magnetic Particle	Dry Powder, Magnetic Particle Inspection: E 109
	Method Spec. for Magnetic Particle Inspection of Large Crankshaft Forgings: A 456
	Reference Photographs for Magnetic Particle Testing of Ferrous Castings: E 125
	Steel Forgings, Heavy, Magnetic Particle Testing and Inspection of: A 275
	Wet Magnetic Particle Inspection: E 138
	Definition of Terms, Symbols and Conversion Factors Relating to Magnetic Testing: A 340
Penetrant Testing	Methods-for-Inspection Liquid Penetrant Inspection of Steel Forgings: A 462
	Method for Liquid Penetrant Inspection of Steel Forgings: A 462

Table A2 (Cont'd)

NDE Method	ASTM Standard and Designation
Radiographic Testing	Industrial Radiographic Standards for Steel Castings (up to 2 inch thickness): E 71
	Tentative Reference Radiographs for Heavy-walled (2 to 4 1/2 inch) Steel Castings: E 186
	Reference Radiographs for Inspection Castings: E 99
	Method for Controlling Quality of Radiographic Testing: E 142
	Recommended Practice for Radiographic Testing: E 94
	Industrial Radiographic Terminology for Use in Radiographic Inspection of Castings and Weldments: E 52
Thickness Testing	Anodic Coatings of Aluminum with Eddy Current Instruments: B 244
	Measurement of Non-Magnetic Coatings of Paint, Varnish, Lacquer, and Related Products Applied on Magnetic Metal Base (Dry): D 1186
	Measurement of Non-Metallic Coatings of Paint, Varnish, Lacquer, and Related Products Applied on Non-Magnetic Metal Base: D 1400
	Measurement of Dry Film Thickness of Paint, Varnish, Lacquer and Related Products: D 1005
	Zinc Coatings on Iron and Steel, Rec. Practice for Use of Magnetic Type Instruments: A 464
	Measuring Coating Thickness by Magnetic or Electro-magnetic Methods: E 216
Ultrasonic Testing	Reference Blocks, Aluminum Alloy. Ultrasonic Standard, Rec. Practice for Fabricating and Checking: E 127
	Reflection Method Using Pulsed Longitudinal Waves Induced by Direct Contact: E 114
	Rec. Practice for Ultrasonic Testing by Resonance Method: E 113
	Rec. Practice for Ultrasonic Testing and Inspection of Heavy Steel Forgings: A 388
	Method and Specification for Ultrasonic Testing and Inspection of Steel Plates of Firebox and Higher Quality: A 435
	Weldments, Ultrasonic Contact Inspection of: E 164

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